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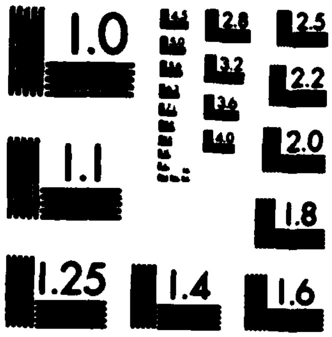

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COOLING SYSTEM DEGRADATION INDICATOR

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Golden

23 January, 1987

Final Report on SBIR Phase I research
Contract Number: DAAE07-86-C-R072

Prepared for
U. S. ARMY TANK AND AUTOMOTIVE COMMAND
Warren, MI 48397-5000

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The Phase I Small Business Innovation Research completed demonstrates the feasibility of determining the cooling system performance of an engine by monitoring two temperature parameters associated with the engine system, ambient air temperature, (TA), and coolant temperature at the coolant exit point from the engine, (TB). The performance of the cooling system was computed through a proposed algorithm with real-time TA and TB as inputs. The inputs were fed into a custom-designed prototype electronic circuit that performed the computation when TB exceeded 205 °F. The output of the circuit was a digital readout of the cooling system performance degradation in percent. The proposed algorithm was shown to be unsuitable for the intended purpose. However, the experimental results led to the discovery of a different algorithm which provided the indication of cooling system

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cont'd performance with TA and TB inputs. The comparison of actual TA and TB to reference values associated with the engine system yielded clear indication of cooling system degradation when the system was intentionally degraded. The degree of degradation severity was also indicated from application of the algorithm.

For the engine system used during Phase I research, the reference TA and TB values were obtained with a calibration test when the cooling system was known to be in good condition. It is envisioned that, under real operating conditions, such reference values will be obtained from the manufacturer's published cooling system performance data.

(Keywords:)

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1 PHASE I RESEARCH OBJECTIVES

1.1 Introduction

Most internal combustion engines rely on a circulating fluid coolant system to maintain a desired operating temperature. Cooling system deterioration can result in major damage or failure of engines and transmissions due to severe overheating. This is a major cause of failure in combat and tactical vehicles. A difficulty is that cooling system degradation occurs gradually. Marginal systems may not be noticed until a demanding situation is encountered (usually at the most inopportune time).

The indirect consequences of engine failure are intolerable in times of emergency or combat. Indirect costs can be unacceptably high with transport of perishable goods or when construction projects are delayed. Direct costs include rebuild or repair of overheated engines, loss of vehicle availability and readiness, decreased operational efficiencies, shortened vehicle service life and increased costs of maintenance materials and manpower. A cooling system degradation indicator could be an important component of a well-run preventative maintenance program.

1.1.1 Cooling System Degradation Concept

First Omega Group, Inc. proposed and completed SBIR Phase I research to determine whether the condition of an engine cooling system could be derived from two temperature parameters i.e., ambient air temperature TA and the engine coolant out temperature TB. A cooling system degradation indicator (CSDI) was constructed for the research. The CSDI was designed to meet the requirements of the Solicitation A86-117.

The First Omega Group, Inc. in response to SBIR Solicitation A86-117 envisioned the possibility of a new instrument for vehicles with liquid cooled internal combustion engines. The instrument monitors and inputs two temperature parameters associated with an operating engine, the ambient temperature TA and the coolant out temperature TB. With the input of TA and TB, the instrument computes a percent degradation of the cooling system performance.

The concept for this instrument postulates that it is possible to derive the performance of an engine cooling system by knowing the following:

Ambient air temperature TA, coolant temperature at the thermostat housing TB and reference TA and TB values obtained from the engine system when in good operating condition.

Actual TA and TB, in conjunction with the reference TA, TB data of a similar engine system, i.e., an engine system with a known good cooling system and is the same type as the engine to be monitored can be used in a mathematical algorithm to compute an indication of the cooling system degradation of the engine of interest.

As a starting point of the research, a particular algorithm for the instrument was proposed and built into the circuitry:

$$\text{Cooling degradation} = [1 - (k/TB - TA)] \times 100\%$$

Where k was envisioned to be a constant which can be set during calibration of the engine system.

1.2 Phase I Technical Objectives

The primary objective of Phase I research was to determine the feasibility of determining the cooling system performance of an engine by monitoring two temperature parameters associated with the system, ambient temperature TA and engine coolant out temperature TB. The cooling system performance was computed through a prototype Cooling System Degradation Indicator (CSDI) circuit that performed a proposed algorithm.

The proposed algorithm built into the CSDI, i.e., cooling degradation = $[1 - (k/TA - TB)] \times 100\%$ was a particular algorithm selected to start the research. We set out to determine the feasibility of deriving the cooling system performance through this and/or other algorithms. That is, to determine whether by mathematical manipulation of TA, TB and some characteristic parameter(s) of a non-degraded reference cooling system, some measure to indicate the performance of the cooling system of interest can be obtained.

1.3 Phase I Work Plan

The administrative, clerical, design, fabrication and analytical activities were performed in the principal offices of the First Omega Group, Inc., at 10205 W.

Exposition Ave., Lakewood, Colorado and at 1667 Cole Blvd. Suite 400, Golden, Colorado.

Arrangements were made with the Agricultural Engineering Research Center (AERC) of Colorado State University to enable access to an engine test cell and associated equipment by First Omega Group, Inc. employees and consultants for the accomplishment of Phase I Research.

The Project Manager for this effort was Charles E. Brossia. Samuel C. Wu served as Research Engineer, Douglas R. Ogden as Electronics Engineer, Donald Baker and Steven Rogowski as research assistants. Dr. Paul D. Ayers, Assistant Professor in Agricultural Engineering, Colorado State University, was consultant to the project manager.

Phase I research consisted of four main work activities:

Preparation Activities
Prototype Design Activities
Fabrication and Testing Activities
Evaluation and Final Reporting Activities

1.3.1 Preparation Activities

Prior to the start of prototype design and experimental designs, the following activities took place under the supervision of the project manager.

1. A detailed design of the research plan and project schedule was prepared.

2. A list of needed items of apparatus and supplies was prepared.

3. Needed items were purchased, leased, or designed and fabricated and made available to the project.

1.3.2 Prototype Design Activities

1. A background and literature search for applicable technologies and components using on-line commercial data bases, local university libraries as well as interview with component vendors.

2. Temperature sensors and flow sensors were evaluated for the CSDI circuit application.

3. The specification of the CSDI was generated by the

project manager.

4. The design of the CSDI circuit was undertaken by Douglas R. Ogden, Electronics Engineer on the project team.

5. Completed the engine test cell modification plan for the experimentations.

1.3.3 Fabrication Activities

1. The First Omega Group, Inc. used its shop facilities to construct the temperature and flow sensors needed for the experiments.

2. The CSDI circuit was constructed at the electronics laboratory of Practical Technology Inc. per the circuit designed by the project team.

3. The modifications to the test engine cell in order to make it ready for experimentation were accomplished by Steven Rogowski at the Colorado State University (CSU) AERC.

1.3.4 Testing Activities

Four sequential sets of experiments were completed for this project. Experiment 1 was intended to provide baseline data of the engine/cooling system apparatus. Experiment 2 was intended to provide data on the apparatus while the cooling system was artificially degraded by reduced air flow area to the radiator. Experiment 3 was intended to provide data on the apparatus while the cooling system was artificially degraded by restriction of coolant flow. Experiment 4 was intended to provide data on the apparatus while the cooling system was artificially degraded by replacement of 50::50 glycol/water coolantmix to 100% water.

1.3.5 Analysis and Reporting Activities

In accordance with the requirements of the research contract, two interim reports were prepared and submitted in addition to this Final Report on Phase I activities.

2 EXPERIMENTAL APPARATUS DESIGN AND FABRICATION

2.1 Cooling System Degradation Indicator (CSDI)

The CSDI is a prototype circuit designed and constructed by the First Omega Group, Inc.. The circuit is designed to input two temperature signals, TA and TB, each with a range of -30 °F to 250 °F, and use them to calculate a proposed equation.

$$\text{Cooling System Degradation} = [1 - k/(TB - TA)] \times 100\%$$

The circuit was constructed in hard wired logic to perform this calculation.

Circuit specification:

$$\text{Output} = [1 - (k/TB - TA) \quad \times 100\%$$

where

TB, TA	input temperatures, 10 mv/°F, 0 volts at 0°F
k	constant, variable and settable over the TB - TA range of 5 < K < 280

circuit displays the output of the equation as a bipolar percentage with a resolution of 0.1%.

The circuit has the following inputs:

Inputs:

TB, TA	temperatures, 10 mv/°F, 0 volts at 0°F, - 30 to 250°F, +/-2.5°F
k	constant, variable and settable over the TB - TA range of 5 < k < 280, resolution of 1 count
% limit set	variable alarm limit setpoint, settable over the range of 0 - 100%, resolution of 0.1%
mode	four position rotary switch, selects 1 of 4 inputs to the digital display: 1. manual output mode 2. automatic output mode

3. k setpoint mode
4. % limit setpoint mode

TB / %	two position switch selects either TB or % signals when in the manual mode
alarm reset	resets the % limit exceeded alarm

The CSDI unit controls is shown in Figure 2.1.

2.1.1 TA Circuit

Five volts and ground are supplied to an LM34 temperature sensor for power supply and reference, respectively. The output of the sensor is connected to R1, a pulldown resistor (to permit operation at negative temperatures) and a LP filter consisting of a precision resistor in U2 and C1. U1A buffers this filtered output and inputs it into an offset/gain circuit, consisting of U1B, U1C and associated circuitry. P1 provides the setpoint adjustment, P2 the gain adjustment. The TA signal is output through U1D to TA OUT and TP1. It is also output to JMP1/1.

2.1.2 TB Circuit

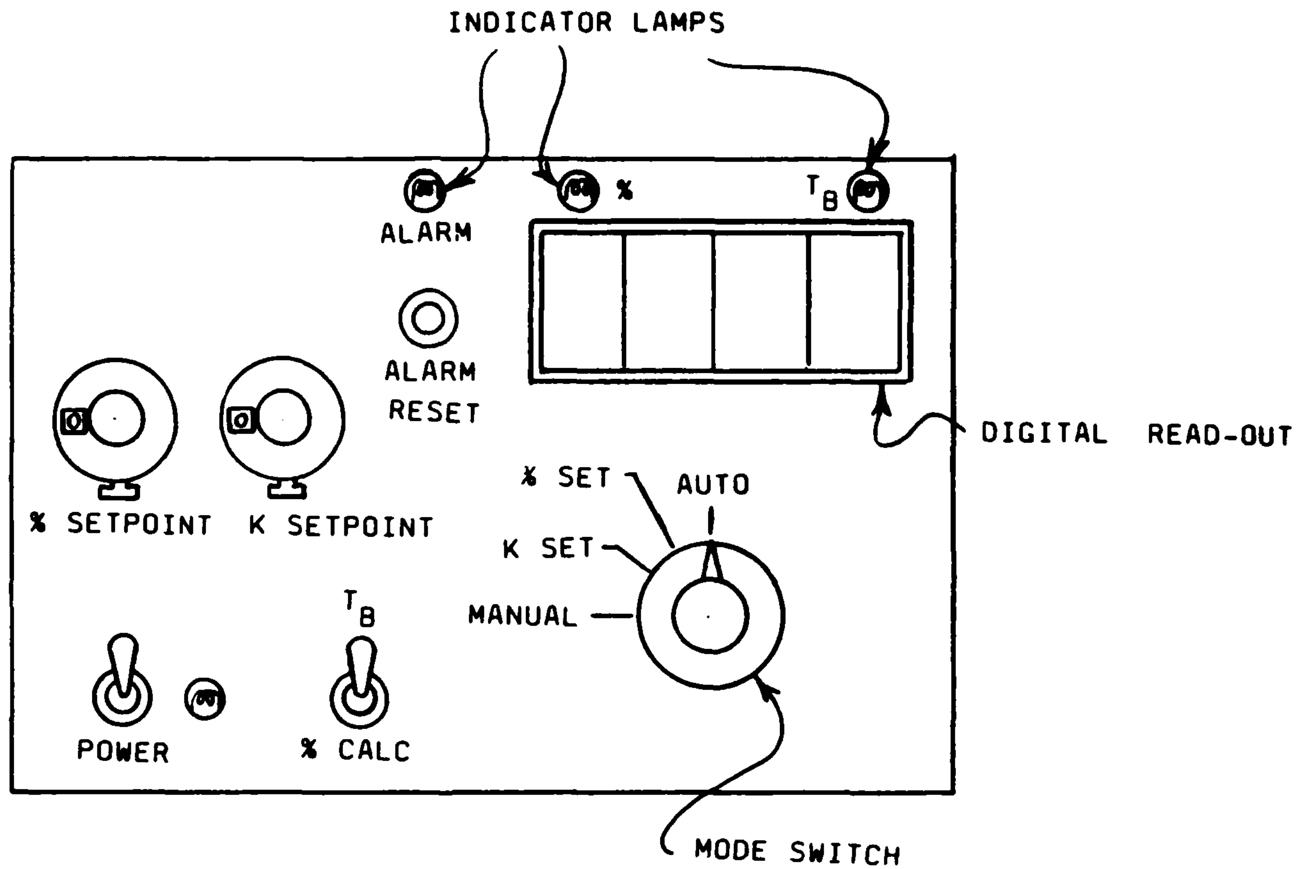
Five volts and ground are supplied to an LM34 temperature sensor for power supply and reference, respectively. The output of the sensor is connected to R4, a pulldown resistor (to permit operation at negative temperatures) and a LP filter consisting of a precision resistor in U7 and C2. U6A buffers this filtered output and inputs it into an offset/gain circuit, consisting of U6B, U6C and associated circuitry. P3 provides the setpoint adjustment, P2 the gain adjustment. The TB signal is output through U6D to TB OUT and TP2. It is also output to JMP2/2.

2.1.3 TB - TA Circuit

U3A performs the TB - TA function using precision resistor network U4. This output is connected to U16D which imparts a gain of 3.5 to the TB - TA signal. This is done to maximize the swing of the signal being input to the division circuit.

2.1.4 K Generation

R55 and CR9 supply a 3.3v reference voltage to a voltage divider consisting of R27, P11 and R28. P11 is used to



COOLING SYSTEM DEGRADATION INDICATOR (CSDI)
by First Omega Group, Inc.

Figure 2.1 CSDI Unit

adjust the maximum value of k. C9 filters this voltage, U13A and associated circuitry invert this signal and feed it to the top of the panel mounted K SET adjustment potentiometer. U13B reinverts and filters the K SET signal, and sends it to two voltage dividers. The 9.8 K SET voltage is divided down to a 0 to 2.80v (9.8 / 35 = 2.80) swing for the digital display. 2.8 volts represents a k of 280. The K SET voltage is also divided down to a 0 to .98v (9.8 / 10 = .98v) swing k signal for input into the divider circuit. This "k / 10" signal accommodates the "10k / (TB - TA)" transfer function of the division circuit. R50 and R51 from the first of the two dividers, dividing the signal by 3.5 x 10 (35) to scale it properly for the digital display. R56, R57 and U9A form the divide by 10 divider and buffer circuit that supplies k/10 to JMP3 jumper and the divider circuit.

2.1.5 Division Circuit

The division circuit consists of U25, a 741 Op Amp, with a four quadrant analog multiplier, U24 in the feedback loop to obtain the division function. The output, available at U25 pin 6 10k / 10k / (TB - TA). This circuit is built as compactly as possible, an housed in a small shielding box. The four potentiometers are adjusted according to the calibration procedure in Appendix A to obtain optimum performance.

The output from the division circuit is input to a setpoint/gain circuit consisting of U9, P5, P6 and associated circuitry. P5 adjusts the setpoint and P6 adjusts the gain. These potentiometers are calibrated according to the procedure in Appendix B.

The properly calibrated -k / (TB - TA) signal is then input to pin 6 of the U4 precision resistor network.

2.1.6 Calculation Circuit

U3D, P13 and associated circuitry provide a P13 adjustable 1.00 volt reference, which is supplied to U4 pin 5. U3B and the U4 precision resistor network accept the inputs of "1" and "-k / (TB - TA)" and perform the addition of these two signals. The output of this addition circuit is made available to the following circuits:

1. Manual mode select switch, CALC % vs. TB
2. U15 inputs, auto mode electronic switch
3. U17B comparator input, detects % LIMIT exceeded

condition.

The 1.00 volt reference is also used by the display driver A/D conversion circuit.

2.1.7 Reference Voltages, Comparators

Resistor R23 and diode CR7 form a 3.3v reference voltage. C6 and U16A filter and buffer this reference voltage, and output it to a dual voltage divider consisting of P9, P10 and fixed resistors.

Potentiometer P9 adjusts the voltage at TP8. This voltage is filtered by C27, and input to the U17A comparator. U17A compares this signal to the TB signal to detect a TB > 2.05 condition. When TB is greater than 2.05, the U17A output goes high, switching the U15 electronic switch from TB to CALC % mode, and switching the corresponding LED, % ON. The TB LED is turned OFF.

Potentiometer P10 adjusts the voltage at TP9. TP9 is the % LIMIT setpoint maximum voltage, and should be set to 1.00 volt. This voltage is routed to the top of the % LIMIT front panel potentiometer. The voltage coming from the % LIMIT potentiometer wiper is routed through the U3C buffer, and input to the U17B comparator. This voltage is then compared to the CALC % signal. When the CALC % signal is greater than the % LIMIT setpoint, the output of the U17B comparator goes high, triggering the U18A latch. The output of this latch, when high, enables a 1 Hz oscillator consisting of U19A, U19B and U19C and associated circuitry. R42 performs a limiting function on the LED2 current. The output from U3C is also routed to SW3-A for input to the digital display.

2.1.8 Output Control, Drivers, Displays

SW2 and SW3 control the input-to-display function; SW2-A selects between CALC % and TB inputs when the manual mode is selected. SW3-A selects between MANUAL, AUTO, SET K and SET %. The output of the switch SW3-A routed through a LP filter consisting of R20 and C5 to the display driver input. Associated resistors and capacitors are connected to the U11 display driver to perform timing and signal conversion functions.

The U11 display driver drives four 7-segment common anode LED displays, connected as a bipolar 3.5 digit display with a decimal point.

U20, U21 and U22, with inputs from SW2-B, SW3-B and SW3-C perform the logic necessary to light the proper front panel LED depending on inputs from these switches and the TB > 2.05 comparator, U17A. Transistors Q1, Q2 and Q3 receive inputs from this circuit and provide the current gain needed to drive the LED's and the decimal point.

2.1.9 Power Supply

Outside power is routed in from the terminal block, through a 1 amp fast blow fuse and to SW1 ON/OFF switch. The switch output is connected to a chassis mounted +5 volt regulator, 7805. The regulator output is routed to the POWER LED, to the +5v supply on the board, and to the inputs of 2 voltage conversion circuits. This regulator is mounted so as to use the chassis as a heat sink.

The first of these two conversion circuits converts +5 volts at the input into -5 volt and -15 volt supplies. The -5 volt output is connected directly to the -5 volt supply on the board via a jumper. The -15 volt output is routed to the input of a -12 volt regulator, 7912. The output of the -12 volt regulator is directly connected to the -12 volt supply on the board.

The second voltage conversion circuit performs a voltage step up function, with an input of +5 volts and an output of +18 volts. This +18 volt output is routed to the input of a +12 volt regulator, 7812. The output of the +12 volt regulator is directly connected to the +12 volt supply on the board.

2.1.10 Outputs

The circuit has 7 outputs, one 3.5 digit bipolar 7-segment LED display,, 4 LED indicators, and outputs for TA and TB. The TA and TB outputs are 10 mv / °F, referenced to ground, and capable of sourcing 10 mA. This makes it capable of driving a modest output, such as the input to a chart recorder.

The 3.5 digit bipolar 7-segment LED display is utilized to display 1 of 4 possible parameters, TB, CALC % (in either the auto or manual modes), K SET, and % LIMIT SETPOINT. TB is displayed to a resolution to the nearest °F. K is set to the nearest unit, and the % is displayed to the nearest tenth of percent.

The four LED indicators are used for POWER % LIMIT EXCEEDED and as mode indicator, CALC % or TB. These LED indicators are color coded in relation to their relative levels of importance.

The entire circuit is mounted in a metal shielded box to reduce noise interference. Figure 2.1 shows the external controls of the CSDI.

2.2 Engine System Preparation

Make:	Allis-Chalmers, Harvey, Illinois
Type:	Liquid cooled, in-line 6-cylinder diesel
Model:	2800
Piston Displacement:	301 cu in
Compression Ration:	16.25:1
Bore:	3-7/8 in
Stroke: cylinder	4-1/4 in 1 intake, 1 exhaust valve per
Water Capacity: (including radiator)	26.5 qt
Governor:	Roosa Master, mechanical centrifugal
Clutch:	Twin Disc Model C-110-HP-3, 10 in diameter single plate
Transmission Gear Ratio:	3.75:1

2.2.1 Pre-Test Engine Maintenance

In order to assure proper condition of the engine and cooling system prior to the initiation of testing, the following maintenance was performed:

1. A new fuel filter was installed.

2. The engine oil was drained, new oil filters (2) were installed and the crankcase was refilled with new oil.

3. A new thermostat and thermostat gasket were installed.

4. The water pump was inspected and cleaned. The seals were replaced and the pump was reinstalled.

5. All radiator hoses were replaced with new ones.

6. The radiator was removed, boiled out, repainted, and reinstalled.

7. The cooling system was filled with a 50/50 mix of water and new ethylene glycol coolant.

2.2.2 Pre-Test Engine Modification

1. A 1.5 in I.D. metal tube was connected to the radiator hose at the outlet of the radiator.

2. A rotary flow meter was installed 27 inch downstream in the tube (specifications in para. 2.5).

3. A screw handle gate valve was located 10 inch downstream of the flow meter.

4. A 26 in long piece of 1.5 in I.D. rubber tubing was attached 5 in downstream of the gate valve. The rubber tubing was bent around in a U-shaped, attached to a 36 inch piece of 1.5 in I.D. metal tube which was installed to the radiator hose attached to the water pump intake.

5. Temperature sensors (specifications in para. 2.5) were installed in the thermostat housing, at the water pump intake and approximately 5 inch in front of the radiator with the aid of a plywood frame.

Figure 2.3 illustrates the sensor locations and modifications.

2.3 Dynamometer Preparation

Make: AW Dynamometer Inc., Colfax, Illinois

Model: 4500

Type: Water cooled, hydraulically controlled brake-type

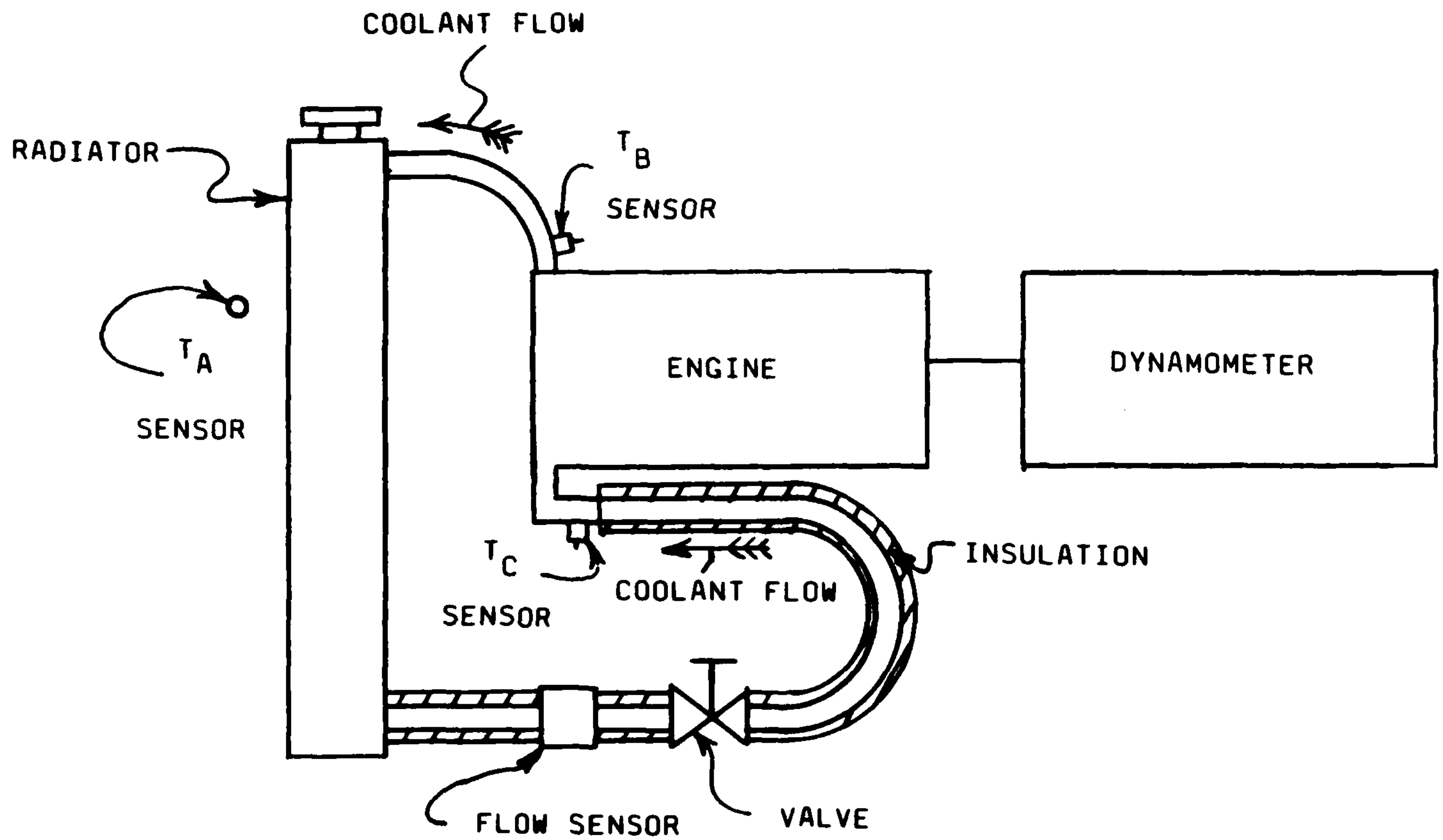


Figure 2.3 Sensor Installation Location

Prior to testing, the dynamometer was inspected for condition, the hydraulic reservoir was filled with oil and the air was bled from the hydraulic lines. The recording cylinder was located at the one foot mark on the torque arm, and the power take off shaft was attached to the output shaft of the transmission.

The engine and dynamometer connection through the 3.75:1 transmission and the dynamometer having a 1-foot torque arm, the following explanation relates engine performance and dynamometer readings:

1. Since the recording cylinder was located at the one foot mark of the dynamometer, the torque reading visually read off the dynamometer was 1/10 of the actual dynamometer torque, represented by the equation:

$$\text{Dynamometer torque (ft/lb)} = \text{(torque reading)} \times 10$$

2. Due to the 3.75:1 transmission, the following equations were used to find the actual engine performance:

$$\text{Engine torque (ft/lb)} = \text{Dynamometer torque(ft/lb)} / 3.75$$

3. Engine horsepower equation:

$$\text{Engine power (H.P.)} = \frac{\text{Engine torque (ft/lb)} \times \text{engine RPM}}{5252}$$

2.4 Ambient Temperature Control Box

A temperature control box was constructed around the engine system for the purpose of accurately controlling the temperature of the air entering the radiator (TA). A sketch of the box is shown in Figures 2.2.

The box basically consists of three chambers. The engine chamber houses the engine, clutch and transmission. A dividing wall was constructed tightly to the radiator such that the radiator is actually not contained in the engine chamber. The radiator, along with the engine air intake, are located in the air mixing chamber. The final chamber is the hot air return chamber where hot air that has been passed through the radiator and over the engine can be transferred to the air mixing chamber.

The temperature control box allows the adjustment of TA by adjustment of the air deflection flaps located on either

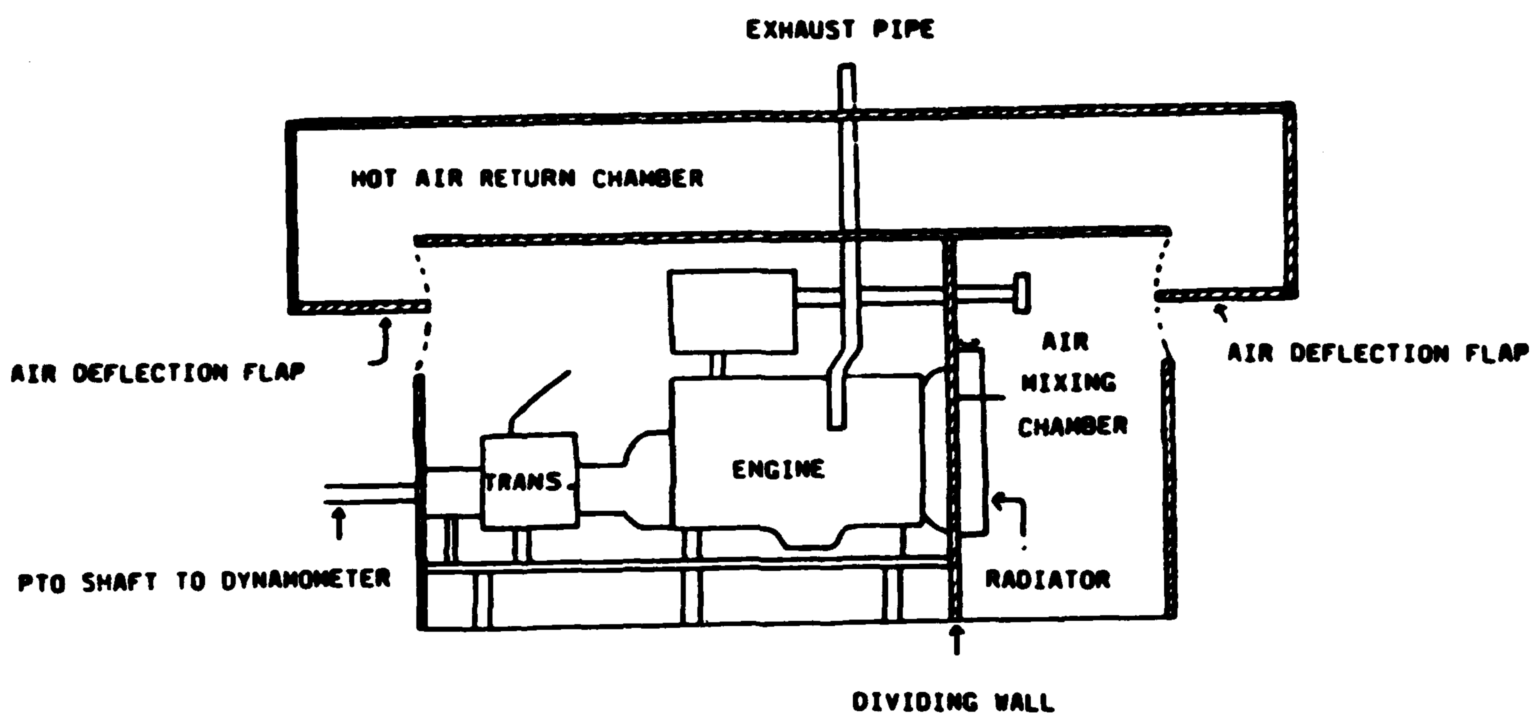


Figure 2.2 Temperature Control Box

end of the box. By adjusting the rear air deflection flap, the amount of hot air that passes through the hot air return chamber can be controlled. By adjusting the front air deflection flap, the amounts of room temperature air and hot return air that enter the air mixing chamber can be controlled and, thus, TA can be adjusted and held constant at various settings.

The temperature control box was primarily constructed with 1/4 in. plywood over 2 x 4 in. framing. The box has three 6 ft x 451/2 in. access doors to allow easy access to the engine and radiator for any service or adjusting that is necessary. A Plexiglas door and a Plexiglas window were installed on one of the access doors so that the engine mounted gauges could be viewed and the throttle, clutch and switch could be reached quickly, if necessary. An emergency off-switch was also installed on the outside of the box in case any emergencies should arise. The exhaust was run through a 2 in. I.D. pipe straight up from the manifold through the top of the temperature control box and then over horizontally through the building wall.

2.5 Data Acquisition System

A Cyborg, Inc. (Newton, Massachusetts) Model SYS.91, ISSAC 91-I data acquisition system (Part No. 850-260, S/N 1117, Rev B) acquired data from sensors and equipment of the test cell apparatus. These included a prototype Engine Cooling System Degradation Indicator (CSDI), S/N 001002, three National Semiconductor LM34 temperature sensors and a Signet Scientific (El Monte, California) flow sensor (P/N MK515-PO, S.N 6031907). An IBM Corporation (Armank, New York) IBM-PC/XT computer (Model 5160, S.N. 54329645160) controlled the ISSAC 91-I with Cyborg LABSOFT control software and a BASICA program. Figure 2.3 illustrates the sensor locations and the coolant flow directions.

The three temperature sensors measured air temperature in front of the radiator, (TA), coolant temperature in the top of the engine block upstream of the thermostat, (TB), and the temperature of the return flow of coolant from the radiator as it entered the engine block, (TC). The sensors for TB and TC were provided with copper tube housings and 1/2-inch NPT fittings to match those available on the engine. The sensor for TA was protected by black heat-shrink tubing.

The Signet Scientific flow sensor in a 1 1/2-inch water pipe t-fitting calibrated by the manufacturer was installed in the coolant flow path. A 25-inch length of 1 1/2-inch water pipe served as an upstream flow straightener for the sensor. See Figure 2.3 - Sensor Installation.

The sensors for TA and TB were connected to and powered by the CSDI. The CSDI provided outputs for TA and TB to the ISSAC 91-I system at 10 mV/ °F. The TC sensor was powered by the +5V logic supply of the ISSAC and also gave readings at 10 mV/ °F. The flow sensor consisted of a four-blade paddle wheel extending into the flow. Each blade incorporated a magnet which was of opposite polarity to the adjacent blades. As the wheel turns, it generates an AC voltage in a coil, proportional to flow in both frequency and magnitude.

The signal from the flow sensor is conditioned by the circuit in Figure 2.4. The circuit is powered by the +15V External Power Supply (Cyborg, Corporation, Model EXT PWR, P/N 850-213, S/N A-32283) of the ISSAC system.

Since there was an accurate calibration constant only for flow as a function of frequency:

Flow (GPM) = 1.095*Frequency (Hz)

and the AC voltage output of the flow sensor had a high harmonic content (not a true sine wave). It was necessary to calibrate the frequency input of the conditioning circuit to its voltage output with the sensor signal in operation. The engine was started and put under load causing coolant to flow in the radiator. The frequency at TP1 was measured with a Fluke Model 1900A frequency counter and compared to the voltage at TP2, measured with a Fluke Model 8024B digital voltmeter. Linear regression then gave an equation of:

$$F = 0.09757437 + 11.66059*V, \text{ where}$$

F = frequency at TP1 (Hz)
V = voltage at TP2 (V), and

the F statistic for the regression was 2925.7. The flow in gallons per minute (GPM) is then:

$$GPM = 1.095*F = 1.095\ (0.097577437 + 11.66059*V)$$

The voltage of TP2 and the circuit ground (power ground) were connected to the ISSAC differential analog input channel 5.

One other conditioning circuit (Figure 2.5) was used to increase the CSDI output for K-SET by a factor of ten. Some

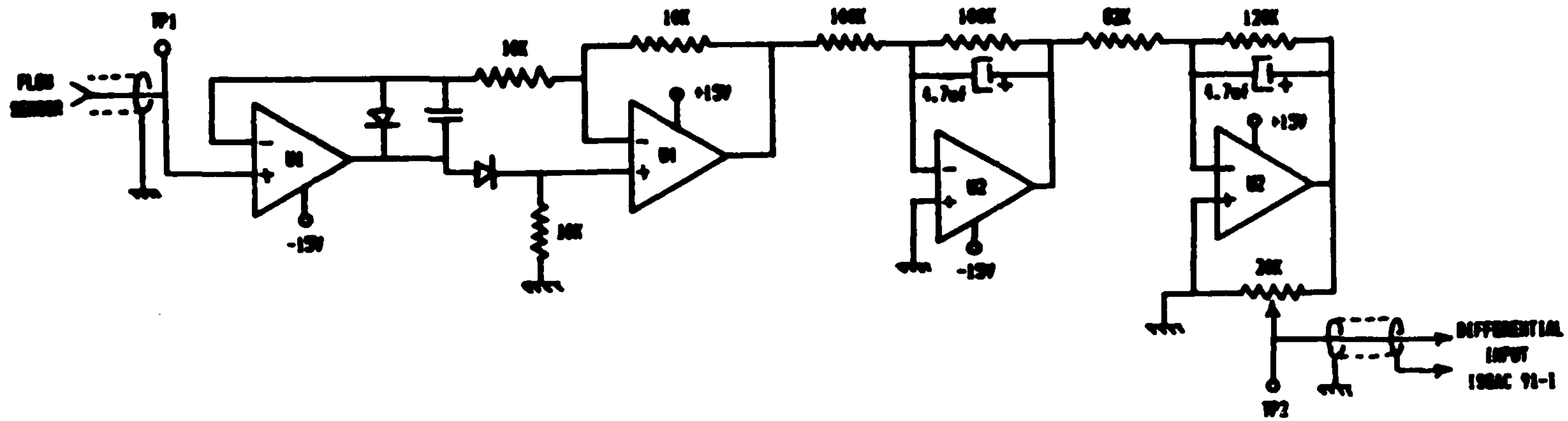


Figure 2.4 Flow Sensor Rectifier

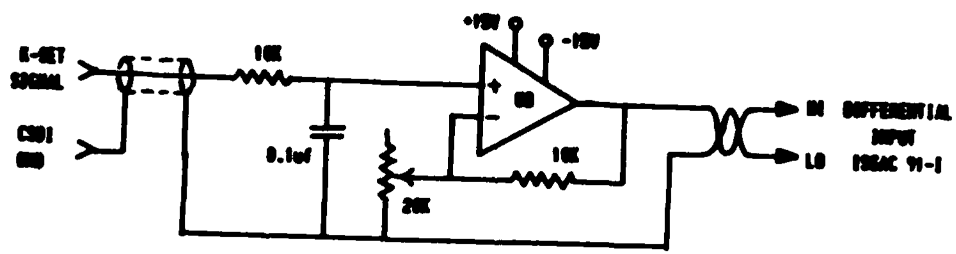


Figure 2.5 K-set Amplifier

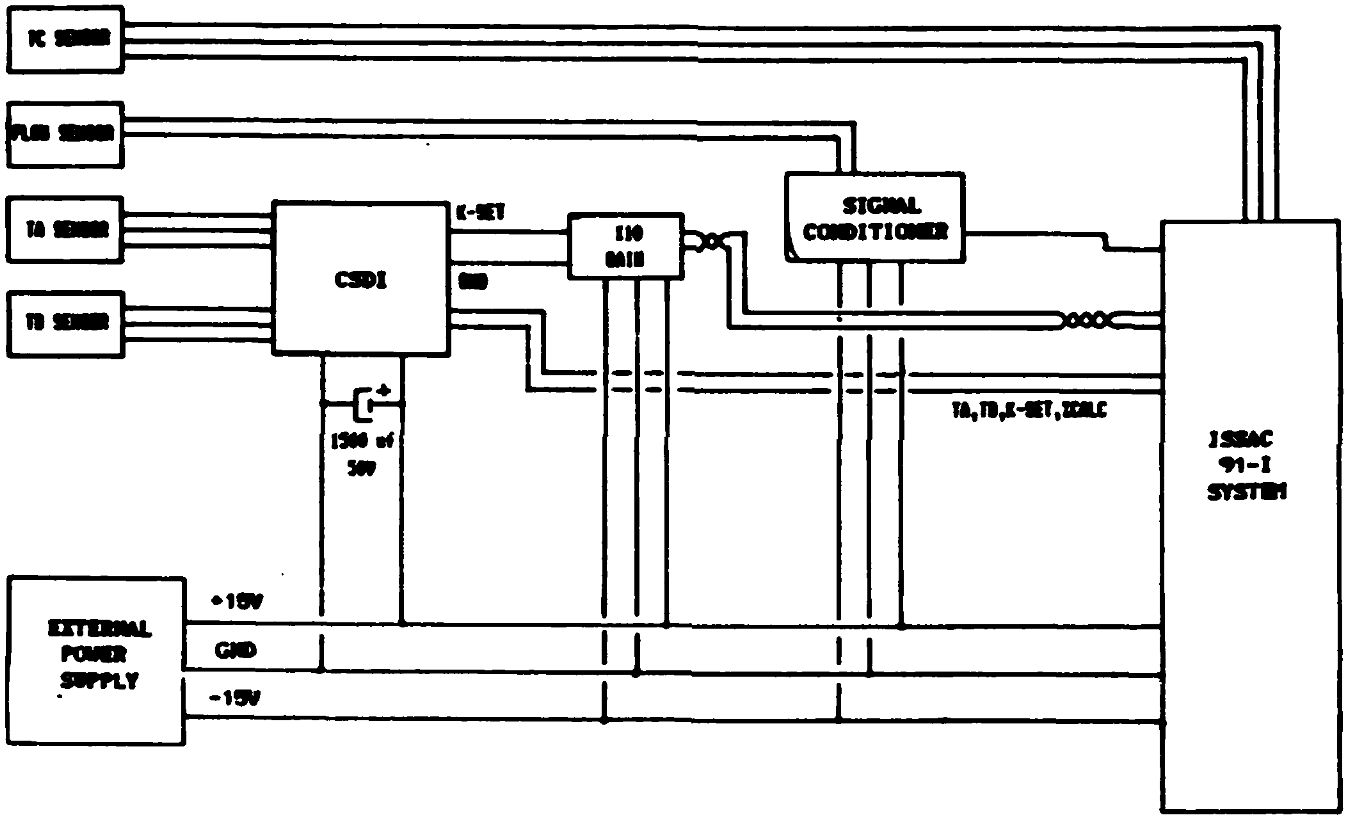


Figure 2.6 Data Acquisition Schematic

capacitors were used at the ISSAC differential analog inputs because of the digital noise from the CSDI.

Of more significance was the digitization noise in the ISSAC (the ISSAC was set to digitize). The ISSAC was set to digitize a 0 to +5V range into values of 0 to 195 (12 bits). According to Cyborg, the ISSAC digitized valve may jitter +5 counts. This means that the reading may vary +6.1 mV. In the temperature readings, this is + 0.61 °F. An even larger variation was seen in practice due to noise from the sensors and CSDI. The readings from the flow meter are somewhat more unsteady (as can be seen in the data plots) due to the nature of the measurement. The data acquisition power and signal connections are diagrammed in Figure 2.6.

3 EXPERIMENTATION

The laboratory testing of the engine system and the Cooling System Degradation Indicator (CSDI) was done in the Agricultural Engineering Research Center (AERC) of the Colorado State University (CSU).

The test engine system with the temperature control box enabled the ambient temperature TA at the radiator air inlet be varied from room temperature to 150 °F. The cooling system of the engine was modified to allow artificial degradation of performance by radiator airflow blockage, coolant flow blockage and coolant dilution by water.

The experimental apparatus is illustrated in Figures 2.1, 2.2 and 2.6.

Figure 2.3 shows the engine system with a modified coolant return passage. It also gives the locations for the temperature and flow sensors. Figure 2.2 illustrates the design of the ambient air temperature TA control box. Figure 2.6 illustrates the data acquisition system signal and power connections.

3.1 Experiment 1 : Baseline Data

The first experiment generated baseline data for engine operation with no simulated degradation in the cooling system. The engine was allowed to warm up. Then at full-throttle and 50 percent load applied (by the dynamometer) data was taken from different settings of ambient temperature from room temperature to 150 °F in 15-degree steps. The ambient air temperature TA was adjusted by regulating the air deflection flaps on the temperature control box. Data was taken both by hand on test run forms and by the IBM-ISSAC system.

The coolant was a 50:50 mix of water and ethylene glycol coolant mix. Tests were conducted with the access doors of temperature control box, (Figure 2.2), latched shut and all ambient temperature adjustments were done with deflection flaps. All of the tests were run with a Dynamometer load such that torque reading on the dynamometer read 33. This correlates to an engine output of 88.0 ft/lb of torque, 2079 rpm and 34.8 HP dynamometer setting is approximately a 50 percent load for the engine.

The following is the basic procedure that was followed for each of the baseline tests:

1. The engine was started and allowed to warm up at low rpm for several minutes.

2. The throttle was adjusted to the wide open position and the dynamometer load was set.

3. The computer program was started and a test report form was started noting the test number and any initial conditions.

4. The engine was allowed to run until the value of TA, TB and TC rolling up on the computer screen had stopped fluctuating.

5. At this point, the K value was adjusted so that the value of percent degradation on the CSDI display was 0.0.

6. The values of K and TB were noted on the test report form.

7. The value of TA on the computer screen was noted and the air deflection flaps were adjusted to a position so that TA was increased by approximately 15 °F.

8. The engine was allowed to operate at this new value of TA. Calculated percent degradation and TB from the CSDI were noted on the test report form along with the time into the test.

9. The value of TA continued to be increased by increments of approximately 15 °F by adjusting the air deflection flaps until TA reached a value of approximately 150 °F. For each of these temperature increments, percent of calculated degradation, TB, TA and time into the test were recorded on the test report form.

10. After the final TA value had been noted, the air deflection flaps were adjusted to the fully open position, the dynamometer load was released, the computer program was terminated, and the engine was run for several minutes before it was shut off.

Any pertinent information on the test or actions taken during the test were noted along with the time on the test report form. Unless otherwise noted, all values of TB on the report forms refer to TB indicated on the CSDI while TA values were taken directly from the computer screen. Generally, when the desired value of TA was reached, the air deflection flaps were not adjusted. TA would generally fluctuate around the desired TA, but would maintain a mean value of the desired temperature. Between tests, a fan was used to blow air across the engine to aid in cooling. The TB reading on the CSDI reached a minimum of 165 °F before the next test was conducted. The data generated for the testing were plotted for Tests 101, 102 and 103. Test 101 represents data taken before the flow sensor and radiator return pipe were insulated with foam wrap. Test 102 is data taken after the pipes were insulated. The test data is presented graphically in Figures 4.1, 4.2, 4.3 and 4.4. Some numerical data and additional graphical plots are included in Appendix B.

3.2 Experiment 2 : Radiator Air Blockage

For the second experiment, the cooling system was artificially degraded by restricting the airflow to the radiator. Twenty five percent (Test 231), Fifty percent (Test 250) and seventy five percent (Test 280) of the radiator's finned surface was blocked with a piece of plywood bolted to the fron of the radiator and blocking it from left to right (facing the engine). This was intended to simulate reduction of the heat ejection capability of the radiator thus degrading the cooling system performance.

The plywood baffle was placed on the front of the radiator before the test was initiated. With the baffle in place, the tests were conducted following the procedure as described in Experiment 1.

The data generated for the testing were plotted for Tests 231, 250 and 280. The test data are presented graphically in Figures 4.1, 4.2, 4.3 and 4.4. Some numerical data and additional graphical plots are included in Appendix B.

3.3 Experiment 3 : Coolant Flow Restriction

For this series of experiments, the cooling system was artificially degraded by reducing the coolant flow cross-sectional area. This was intended to simulated the effects of a defective water pump or of a slipping drive belt. The coolant flow restriction was achieved by the use of the 1.5in. I.D. screw handle gate valve located downstream of the flowmeter on the radiator output stream

(Figure 2.3). The gate valve was used to restrict the cross-sectional area of the 1.5in. I.D. flow pipe a specified amount. The flow area of the gate valve was reduced 10 percent (Test 310), 26 percent (Test 320), 40 percent (Test 340) and 60 percent (Test 360).

As in the radiator blockage tests, the restrictions were imposed before the tests began. The tests were then conducted under the same procedure as is described in Experiment 1.

The data generated for the testing were plotted for Tests 310, 320 and 360. The test data are presented graphically in Figures 4.1, 4.2, 4.3 and 4.4. Some numerical data and additional graphical plots are included in Appendix B.

3.4 Experiment 4 : Coolant Degradation

For this test, the cooling system was artificially degraded by altering the coolant composition of the system. The 50 percent ethylene glycol-water mixture was drained from the radiator and engine block and was replaced with ordinary tap water. The test was then run following the procedures outlined in Experiment 1.

The data generated for the testing were plotted for Test 401. The test data are presented graphically in Figures 4.1, 4.2, 4.3 and 4.4. Some numerical data and additional graphical plots are included in Appendix B.

4 RESULTS AND OBSERVATIONS

A large number of data points were obtained through the test runs. Representative experimental data are presented in Tables 4.1 through 4.10, in addition, the data is presented in graphical form in this section for ease of interpretation.

4.1 CSDI Performance

1. The value for % CALC was negative for all tests (Tables 4.1 through 4.10). This occurred because TA increased more rapidly than TB in the test environment. There was much more thermal inertia associated with the coolant temperature TB than that of the ambient air mass represented by TA in the engine system. This difference caused the quantity (TB - TA) to be negative and thus caused the resultant computed % CALC to be negative.

   The test result indicated that the proposed algorithm:

   cooling system degradation = [1 - K/(TB - TA)] x 100%

   was not usable in this test situation. However, a simpler form of the algorithm was developed from the experimental data. This is discussed in the end of this section.

2. The value for TB displayed by the CSDI while in the manual mode was approximately 3 °F less than temperature indicated by the voltage at TB out test point of the unit. This appears to be an electronic offset and could easily be adjusted.

3. A lack of stability of the electronics in the CSDI was observed. The alarm indicator light would sometimes trip when percent of calculated degradation was not at the alarm level when setting the K value, the percent degradation display would sometimes drift.

4. From our observations, all other features of the CSDI operated according to the designed theory of operation (Section 2).

Table 4.1 Test 101

TA	TB	TC	TB-TC	%CALC
78	191	169	22	0
94	194	178	16	-10.1
112	195	181	14	-23.5
128	199	190	9	-37
151	204	196	8	-50
131	202	193	9	-40
113	197	186	11	-25
99	195	183	12	-15
88	194	181	13	-4.6
83	191	175	16	-3.6

Table 4.2 Test 102

TA	TB	TC	TB-TC	%CALC
78	191	172	19	0
91	193	176	17	-7
104	194	179	15	-16.2
124	197	185	12	-34
137	199	190	9	-48
151	204	198	6	-52

Table 4.3 Test 231

TA	TB	TC	TB-TC	%CALC
82	193	173	20	0
97	195	180	15	-10.4
112	197	185	12	-18.6
130	198	189	9	-36.5
142	199	191	8	-49.4
149	203	196	7	-49.8

Table 4.4 Test 250

TA	TB	TC	TB-TC	%CALC
82	194	176	18	0
95	198	187	11	-7.4
111	199	190	9	-15.3
129	203	195	8	-29.9
148	207	201	6	-49.5

Table 4.5 Test 280

TA	TB	TC	TB-TC	%CALC
76	197	185	12	0
97	207	200	7	-6
106	209	202	7	-60

Table 4.6 Test 310

TA	TB	TC	TB-TC	%CALC
70	191	170	21	0
93	194	178	16	-13.8
110	195	181	14	-30.8
131	197	188	9	-48.5
152	207	200	7	-52.1

Table 4.7 Test 320

TA	TB	TC	TB-TC	%CALC
76	192	171	21	0
87	193	176	17	-6.4
105	194	179	15	-21.5
125	195	182	13	-40.5
137	197	187	10	-49.6
150	202	194	8	-50

Table 4.8 Test 340

TA	TB	TC	TB-TC	%CALC
70	190	169	21	0
97	193	177	16	-16.3
114	194	180	14	-26
136	198	188	10	-48
152	206	199	7	-53.6

Table 4.9 Test 360

TA	TB	TC	TB-TC	%CALC
69	191	170	21	0
92	194	179	15	-11
106	195	181	14	-23.5
129	196	185	11	-40
141	202	193	9	-50
152	209	201	8	-52.3

Table 4.10 Test 401

TA	TB	TC	TB-TC	%CALC
75	190	161	29	0
95	193	174	19	-13
110	195	181	14	-27.8
124	196	185	11	-37
146	200	191	9	-49.6
160	207	202	5	-52.3

4.2 Cooling System Performance

From the test data, we observed the following:

1. At the start of the experiment, the radiator outlet temperature, TC, rises as the engine coolant out temperature TB, until the thermostat begins to open at about 165 °F. Then TC drops about 35 °F.

2. The action of the thermostat is shown in the "Temp. Voltages vs. Time " curves in appendix B. TB is the coolant temperature at upstream of the thermostat and TC is the temperature at downstream of the thermostat. For baseline test 101 the curve is shown on page B-3. It is seen that TC begins to decrease at about 165 °F indicating the beginning of thermostat opening. TB begins to level off and TC reaches it lowest inflection point at about 187 °F indicating the thermostat is fully opened.

3. The plot of TB-TC vs. TA (Figure 4.1), exhibits a significant lowering of the curves for Tests 250 and 280 from the general trend. This confirmed that the ability of the cooling system to lower the coolant temperature was significantly reduced as the radiator airflow was restricted. In Figures 4.2 and 4.3, the values for TB and TC for Tests 250 and 280 show a significant rise from the general trend. This indicates that for a given TA, TB and TC are greater for a degraded cooling system. Figure 4.4 indicates that TB-TA values are also greater for a degraded cooling system. Also, as shown on Figure 4.4, the greater the cooling system degradation, the larger the (TB - TA) vertical distance to the reference line. This shows the possibility of both indicating a degraded system and the amount of the degradation.

4.3 Conclusions

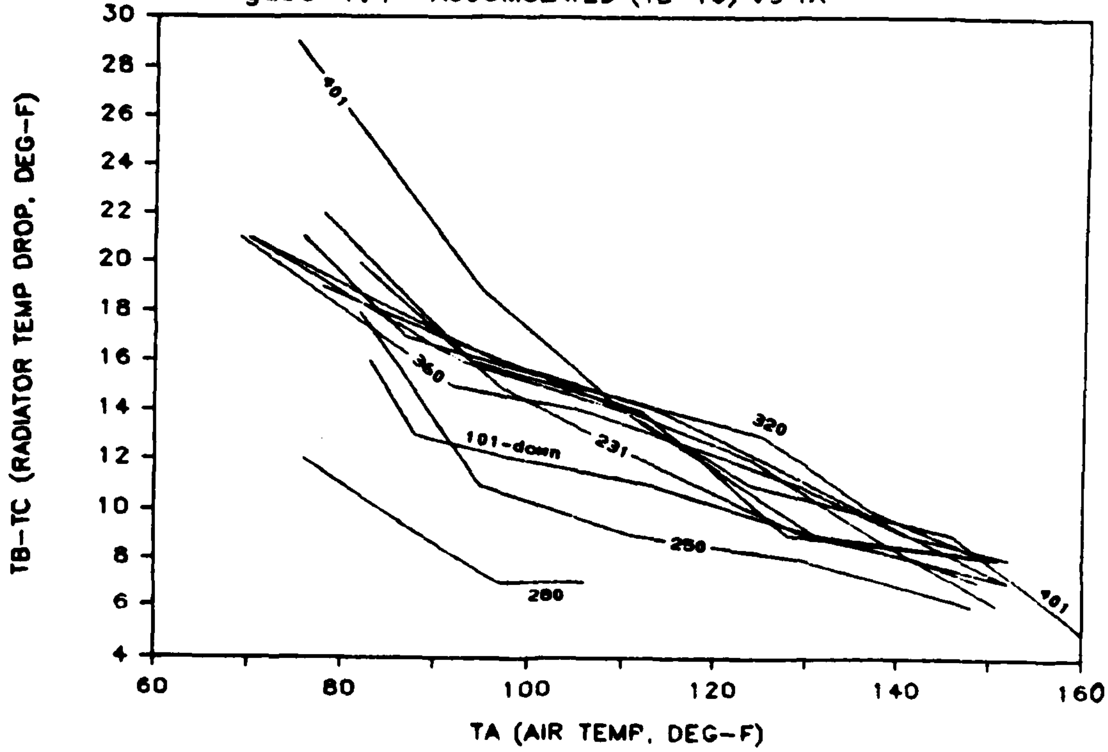
4.3.1 CSDI Circuit

Except for the occasional lack of stability of the prototype circuit, the circuit performed well as designed. From the testing results of the system it was obvious that the proposed algorithm built in the circuit:

$$\% \text{ degradation} = [1 - K/(TB - TA)] \times 100\%$$

was not workable. Since the circuit was built in hard wired logic, it was not possible to modify the math

Figure 4.1 ACCUMULATED (TB−TC) VS TA



TA = ambient temperature
TB = engine out coolant temperature
TC = radiator out coolant temperature

Figure 4.2 ACCUMULATED TB VS TA

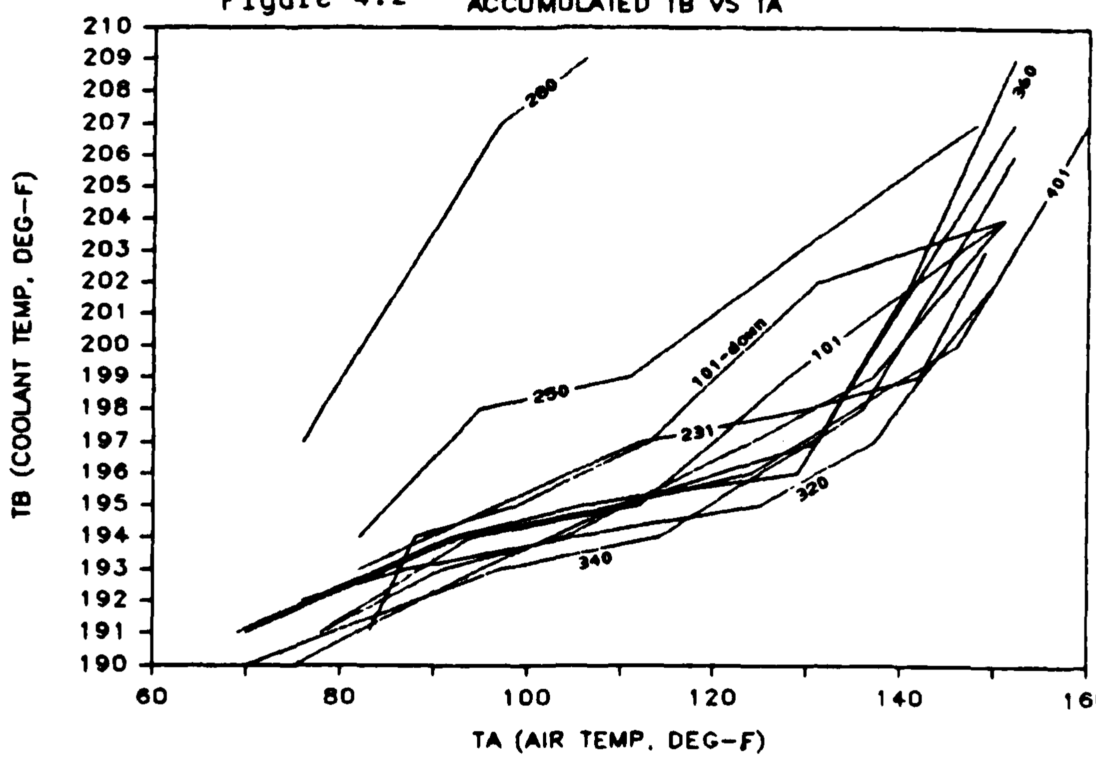
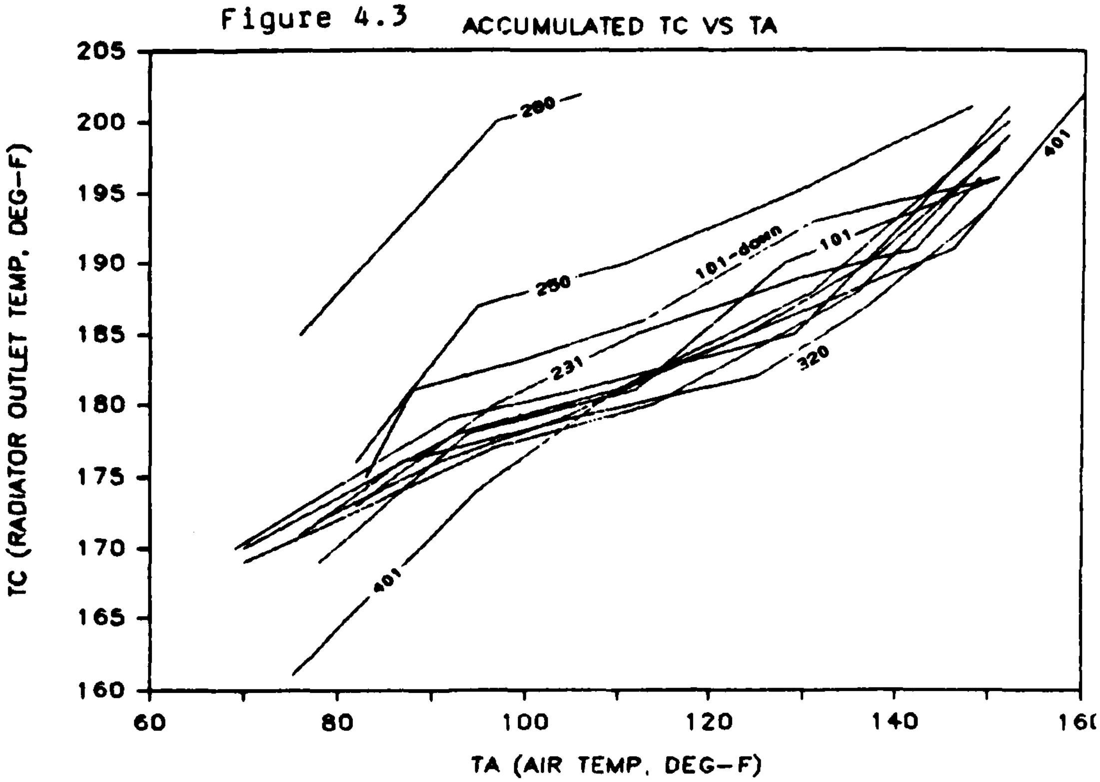


Figure 4.3



TA = ambient temperature
TB = engine out coolant temperature
TC = radiator out coolant temperature

algorithm in the circuit without totally rebuilding the unit.

The CSDI circuit could be made much more versatile if the circuit was to be based on programmable logic integrated circuit chip such as EPROM. This way, modifications to the equation and control logic could be accommodated with software or firmware changes without major hardware modification.

4.3.2 Degradation Indicator Concept

Because the proposed equation :

$$\text{\% degradation} = [1 - K/(TB - TA)] \times 100\%$$

did not work as intended, we set out to determine from the test data whether there was a correlation between TA and TB. The Experiment 1 Test Data of a non-degraded system (100 series), where the cooling system was in known good working order, were analyzed. The data points were subjected to a least squares curve fitting analysis. The following relationship was obtained:

$$TB = 180.3 + 0.1375\ TA \ldots\ldots (R^2 = 0.96)$$

or:

$$TB - TA = 180.3 - 0.8625\ TA$$

This relationship was plotted on Figure 4.4 TA vs TB-TA. The line represents the linear relationship when the cooling system was not degraded. On the same figure, the actual TA vs TB-TA relationship were also plotted for degraded cooling systems. The data for this were obtained from Tests 250, 280,i.e., with radiator airflow 50 percent restricted and 75 percent restricted respectively . Since overheating of an engine generally occurs only when TB is greater than 190 °F, data points used were those after the thermostat was opened, at TB greater than 190 °F. It was noted that the data from the degraded cooling systems consistently plotted above the solid line. Thus the line and the area below it can be considered the safe zone for the cooling system performance. When the actual (TB - TA) points plotted above the safe zone, a degradation of the cooling system performance was indicated. The severity of the degradation was also evident from the plotted points. The larger the vertical distance of the plotted points from the safety zone, the greater the percent cooling performance degradation.

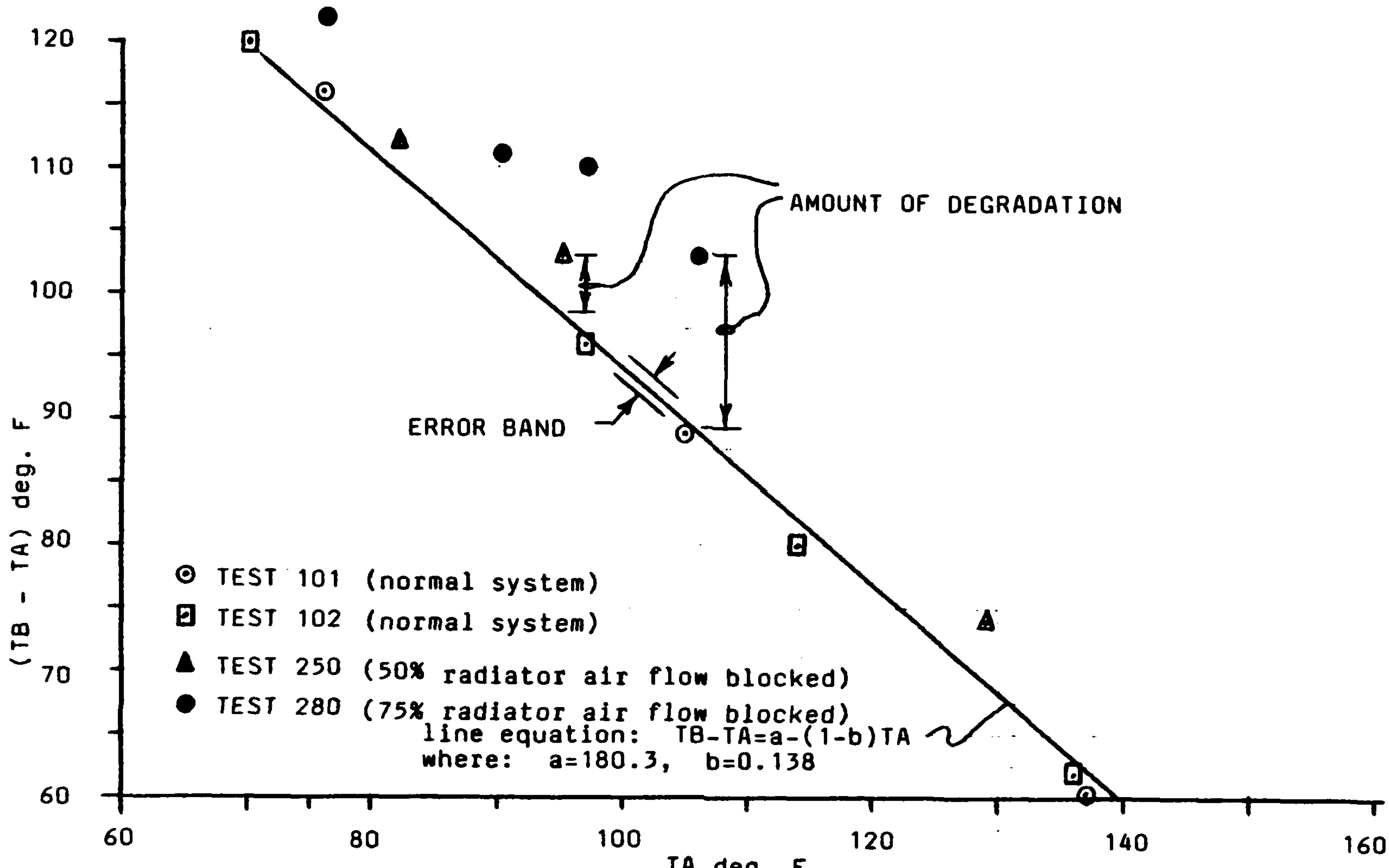


Figure 4.4 TA vs. TB-TA Indication of Cooling System Performance

5 ESTIMATE OF TECHNICAL FEASIBILITY

As shown in the previous section, we concluded that an indication of how well a cooling system is performing can be derived from two actual temperatures associated with the engine system, ambient air temperature (TA) and engine coolant temperature at the thermostat (TB). It was shown in Phase I research that the value of the difference between actual (TB -TA) and the reference (TB - TA) is related to the degree of cooling system degradation, the larger this difference, the more the degradation. The results of testing in Phase I research suggested that a linear relationship exists between TA and TB for a given level of cooling system performance. The relationship was shown to be in the form:

$$TB = a + bTA$$

or

$$TB - TA = a - (1-b)\ TA$$

where a and b are numerical constants derived from actual testing of the engine system.

5.1 Concept Feasibility

In Figure 4.4 (repeated on next page), the solid line represents a plot of the equation:

$$TB - TA = a - (1-b)\ TA$$

where the test engine constants were : a = 180.3 and b = 0.1375. When the cooling system was in good operating condition (Test 101, 102), the (TB - TA) points match the solid line within a narrow error band. As the cooling system was intentionally degraded by incremental blocking of airflow to the radiator, the actual (TB - TA) points shifted to above the line (Test 250, 280) at various values of TA. The greater the cooling system performance degradation (blocking of radiator airflow), the farther the (TB - TA) points shifted to above the line. Thus the location of the actual (TB - TA) points on the graph provides the means to indicate the performance degradation of a cooling system. It can be said that the solid line and the area below it graphically represent the "safe zone" of the cooling system performance. The area above the "safe zone" represents area where the cooling system performance is degraded. The amount of degradation is indicated by the vertical distance of the (TB - TA) points above the "safe zone" line.

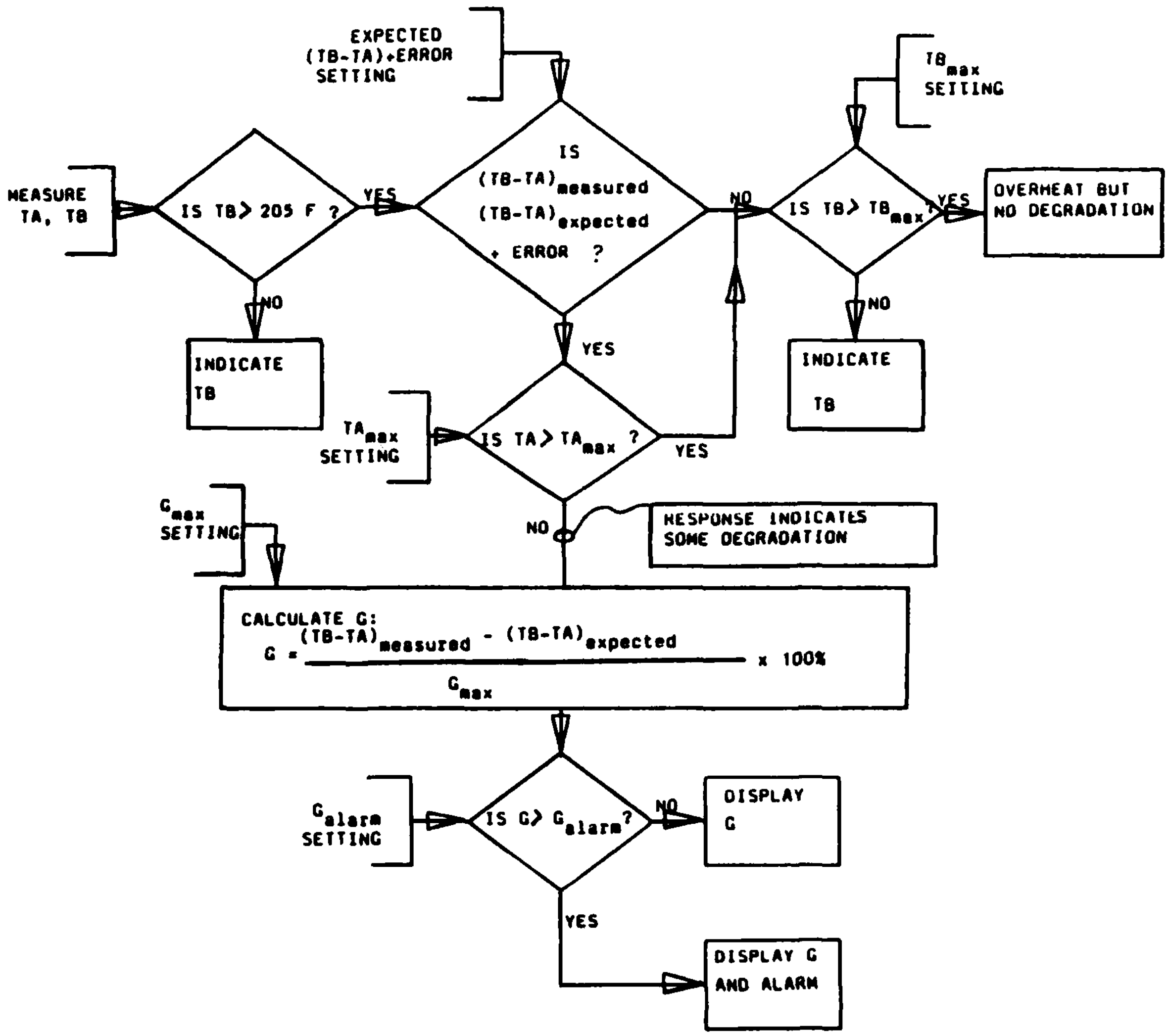
From this graphical representation, we see that it is feasible to determine the existence of degradation in a cooling system and that the severity of the degradation can also be graphically observed. The only inputs needed for such an algorithm were ambient air temperature (TA) and coolant temperature at the thermostat housing (TB). Thus it was demonstrated that the temperature difference between coolant temperature (TB) and ambient air temperature (TA) can be used as a measure of the existance and the severity of the cooling system degradation through the algorithm represented graphically in Figure 4.4.

We are confident that an instrument system intended to monitor the cooling system performance of an engine can be designed based on the above described relationship. This instrument will monitor the coolant temperature normally, acting as the coolant temperature indicator. At coolant temperature above 205 °F, the instrument calculates the cooling system degradation. The calculated degradation is then compared to a preset maximum allowable degradation. Alarm signals will be given to the vehicle operator if the preset degradation value is exceeded. The system logic concept for this proposed instrument is depicted in Figure 5.1.

It is envisioned that, for each particular engine and cooling system combination, a calibration of the instrument can be performed by the manufacturer or rebuilder, i.e., calibration when the engine cooling system is in good condition. For each engine system when new or in good condition, reference values of (TB - TA) at various TA will be obtained similar to that depicted on Table 4.1. These values will be stored in read only memory (ROM) or erasable-programmable read only memory (EPROM) integrated circuits in the instrument to provide reference (TB - TA) valuesneeded for the computation algorithm.

It is possible that such reference (TB -TA) values may also be derived from published cooling performance data from the engine manufacturer.

We believe that a new type of engine instrumentation that indicate cooling system performance degradation can be based on the demonstrated concept from the Phase I research. We estimate the probability of technical success for the design and fabrication of workable, real-world applicable prototypes based on this concept to be in excess of 90%. This field tested pre-production instrumentation can be developed in a Phase II SBIR effort.



WHERE:

ERROR = ALLOWABLE MEASURED ERROR BAND

TA_{max} = MAXIMUM RATED AMBIENT TEMPERATURE

TB_{max} = MAXIMUM ALLOWABLE COOLANT TEMPERATURE

G = PERCENT COOLING SYSTEM DEGRADATION

G_{max} = PRESET MAXIMUM ALLOWABLE DEGRADATION

G_{alarm} = DEGRADATION VALUE SET TO ACTIVATE ALARM

Figure 5.1 New Instrument Logic Concept

Appendix

APPENDIX A PROTOTYPE CSDI PARTS LIST

ITEM	DESCRIPTION	VALUE	REFERENCE DESIGNATORS
	Resistors		
1		1.0 ohm	R201,R202,R203
2		10	R30
3		100	R23,R46
4		1K	R51,R56
5		10K	R2,R5,R31,R36,R37,R104
6		100K	R1,R4,R21,R41
7		1M	R20,R40
8		1.1K	R26
9		1.2K	R25
10		1.3K	R102,R103
11		1.6K	R101
12		1.8K	R24
13		12K	R105,R206
14		150	R205
15		180	R204
16		18K	R106
17			N/A
18		2.2K	R47,R54
19		220	R43,R44,R55
20		220K	R60
21		22K	R61,R62
22		3.3K	R33,R39
23		34K	R50
24		330	R35
25			N/A
26		430	R108,R109
27		470	R110,R111
28		47K	R22,R52
29		4.7M	R32,R58
30		6.8K	R
31		820	R48
32			N/A
33		96K	R3,R6
34		9K	R57
35			N/A
	Integrated Circuits		
36	OP AMP,QUAD	TL074	U1,U3,U6,U13,U16
37	resistor network	100K,ISO	U2,U4,U5,U7,U8,U12,U14
38	resistor network	10K,ISO	U23
39	A/D converter	ICL7107PL	U11
40	OP AMP,precision	MC1741	U9,U9A,U25
41	latch	CD4013	U18

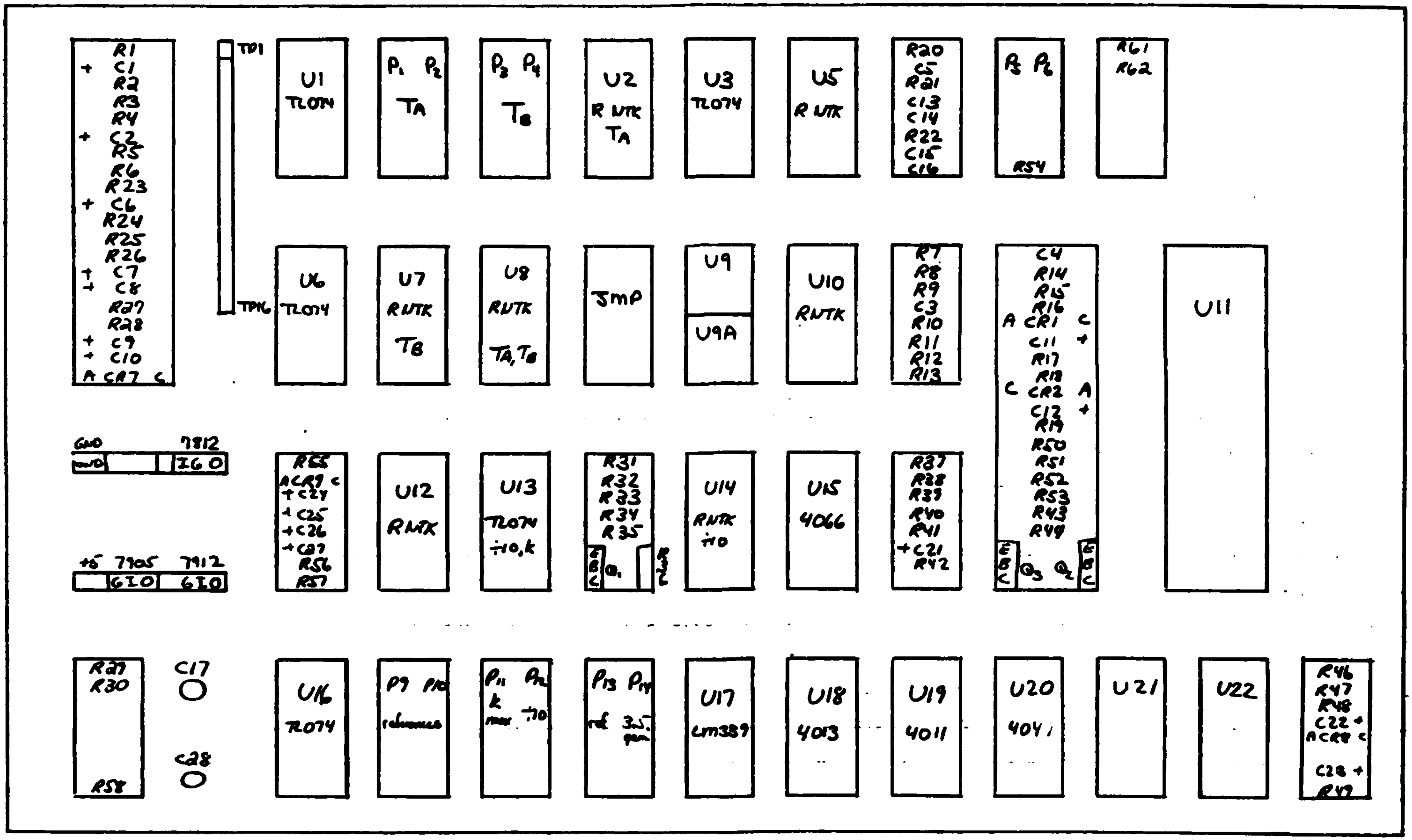
42	OP AMP,QUAD	CD4011	U19
43	hex inverter	CD4049	U20
44	OP AMP,QUAD	CD4071	U21
45	OP AMP,QUAD	CD4081	U22
46	4 QUAD ANALOG MULT	MC1495ML	U24
47	SW regulator	78540	U26
48	QUAD COMPARATOR	LM339	U17
49			N/A
50	potentiometer,10T	1K	P14,P16
51	potentiometer,10T	5K	P2,P5,P12,P14
52	potentiometer,10T	10K	P5,P17,P18
53	potentiometer,10T	50K	P1,P3,P6
54	potentiometer,10T	250K	P9,P10,P13
55			N/A

Capacitors

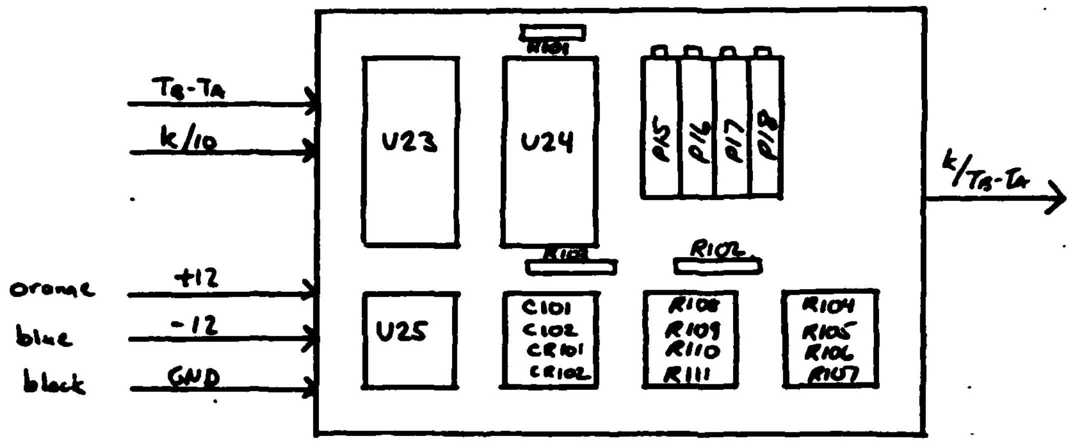
56	tantalum	0.1 uf	C5,C10,C16
57	tantalum	1.0	C9,C100,C101,C102,C103
58		10	C1,C2,C6,C7,C8
59		0.1	C13
60		.47	C14
61		.22	C15
62	tantalum	2.2	C23,C24,C25,C27
63		100	C17,C203
64		.01	C201,C202
65		.47	C21
66			N/A
67			N/A
68			N/A
69			N/A
70			N/A

Other Components

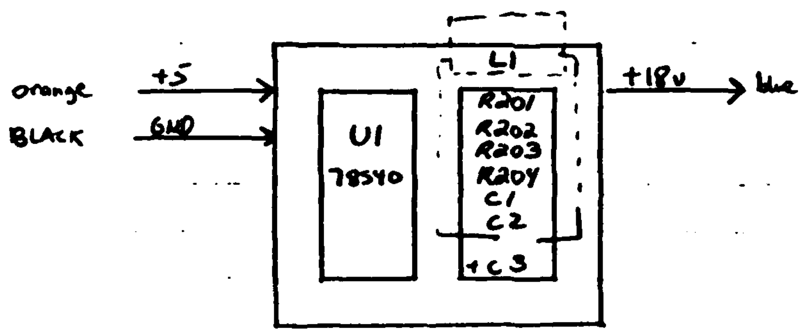
71	voltage reg,+5V	7805T	VR1
72	voltage reg,-12V	7912T	VR2
73	voltage reg,+12V	7812T	VR3
74			N/A
75	transistor,PNP	2N3904	Q1,Q2,Q3
76			N/A
77	diode,zener,3.3V	1N7Y6	CR8,CR101,CR102
78	diode,switching	1N4002	
79	diode,zener,10.0V		CR9
80			N/A
81	inductor	360uHz	L1



Component Placement Diagram (main circuit board)



FOUR QUADRANT MULTIPLIER CIRCUIT



VOLTAGE STEP-UP CIRCUIT

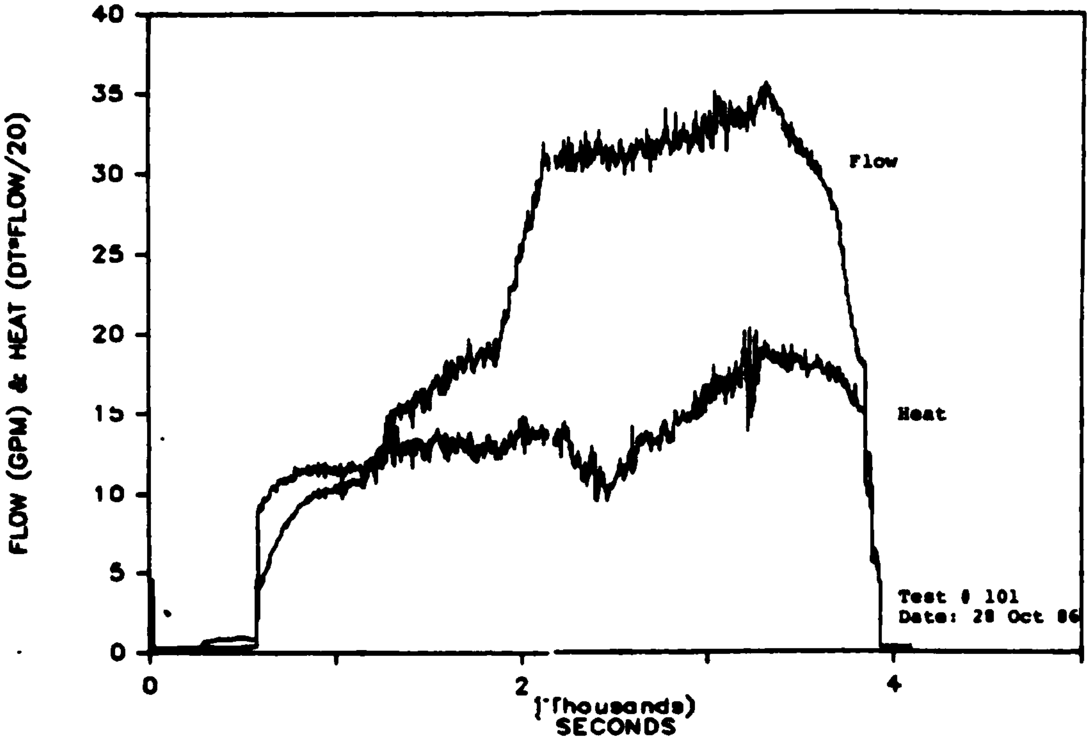
Component Placement Diagram

APPENDIX B - Experimental Data Graphs

EXPERIMENT ONE

BASELINE TEST - RADIATOR RETURN UNINSULATED

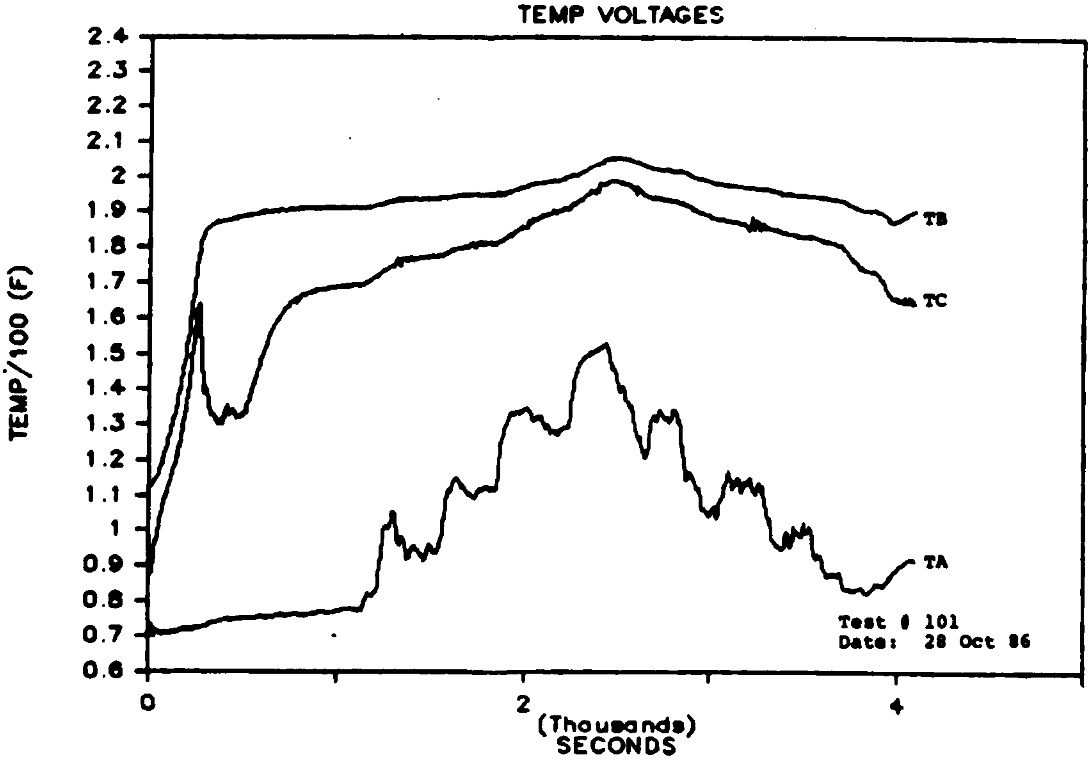
RADIATOR FLOW & HEAT



EXPERIMENT ONE

BASELINE TEST - RADIATOR RETURN UNINSULATED

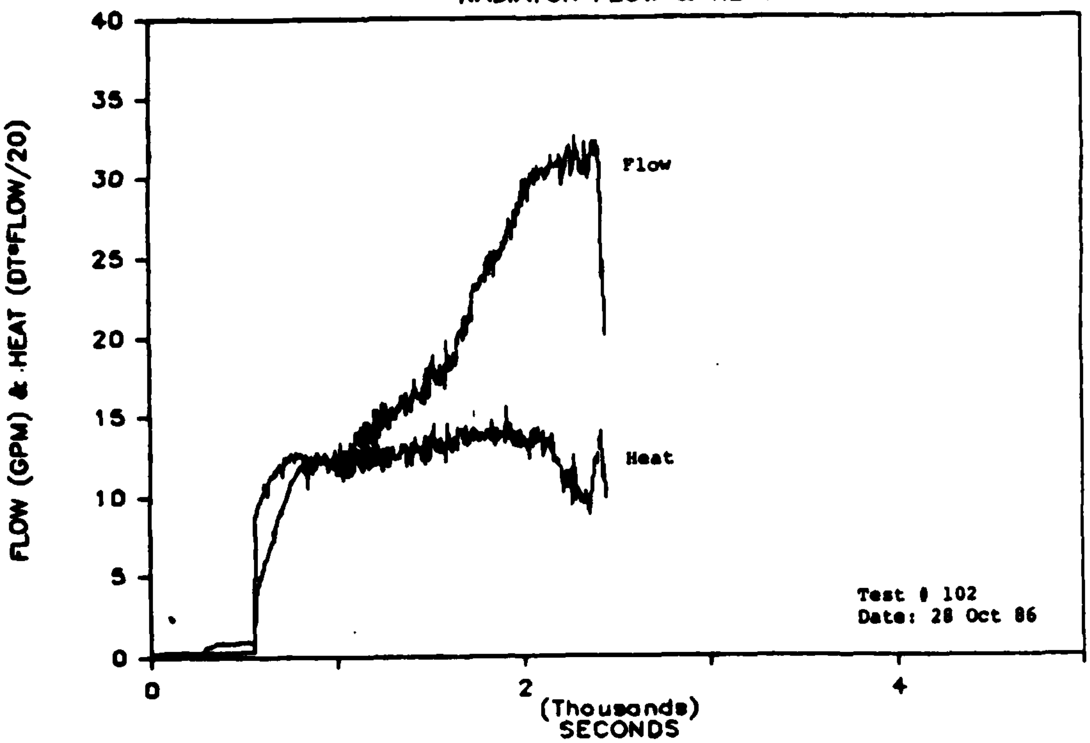
TEMP VOLTAGES



EXPERIMENT ONE

BASELINE TEST - RADIATOR RETURN INSULATED

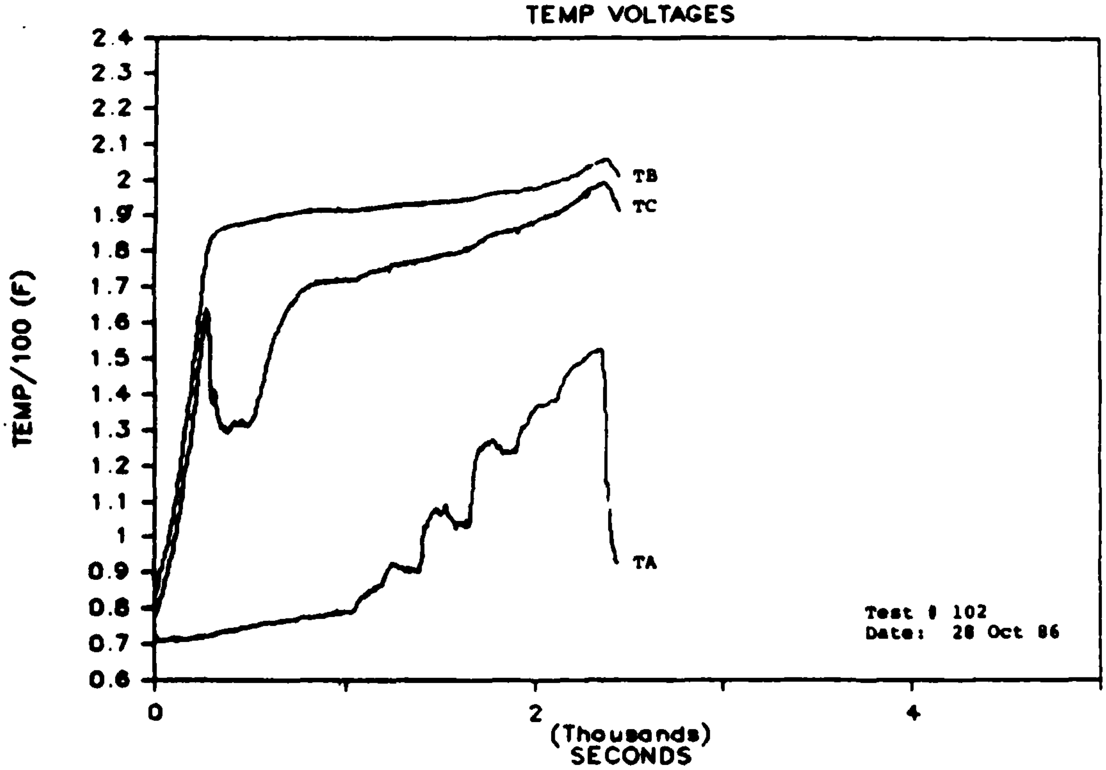
RADIATOR FLOW & HEAT



EXPERIMENT ONE

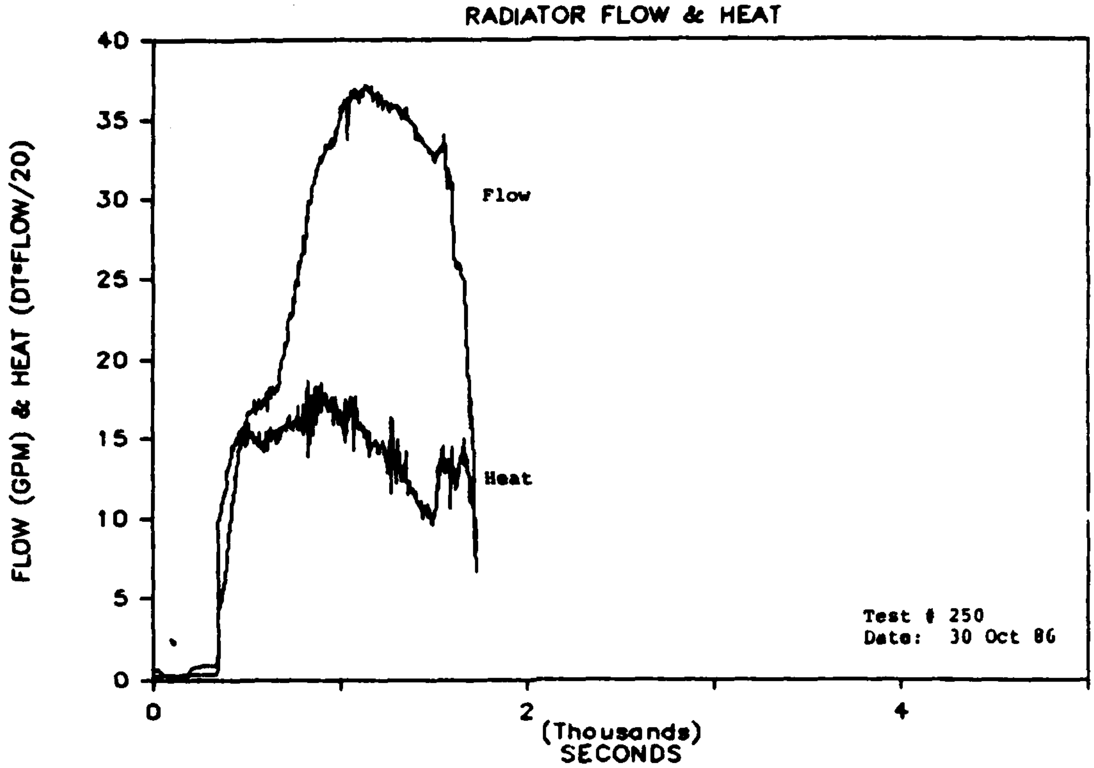
BASELINE TEST - RADIATOR RETURN INSULATED

TEMP VOLTAGES



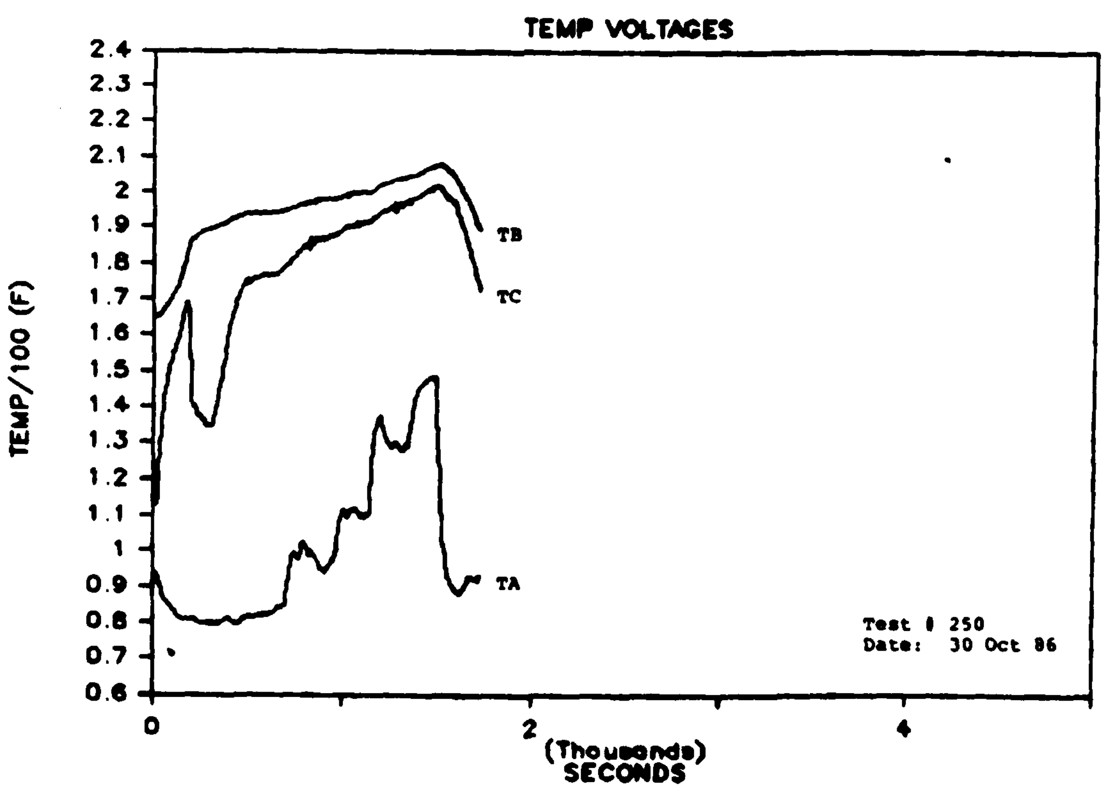
EXPERIMENT TWO

RADIATOR AIR 50% BLOCKED



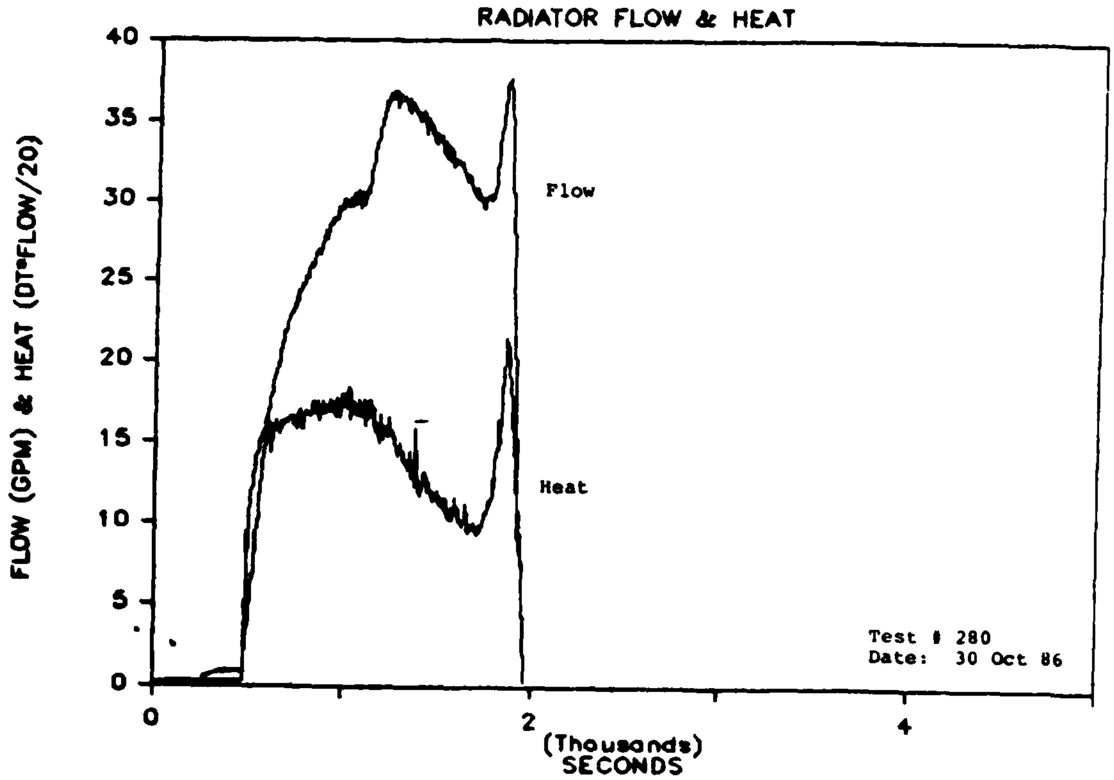
EXPERIMENT TWO

RADIATOR AIR 50% BLOCKED



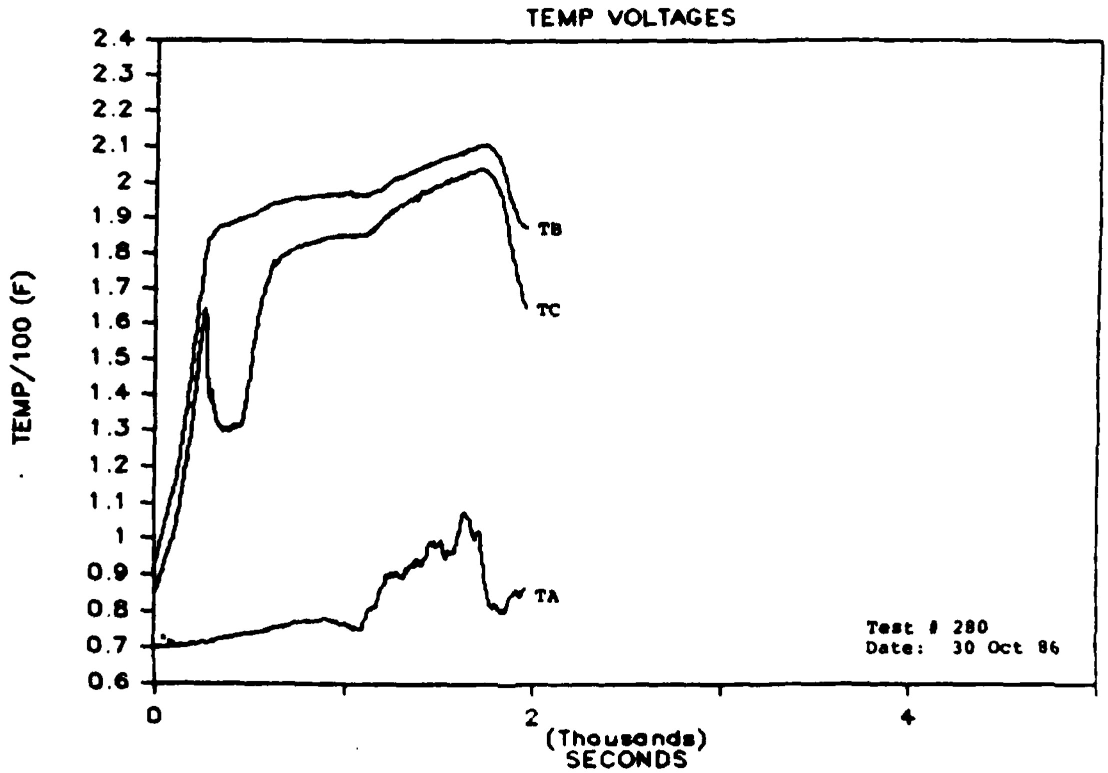
EXPERIMENT TWO

RADIATOR AIR 75% BLOCKED



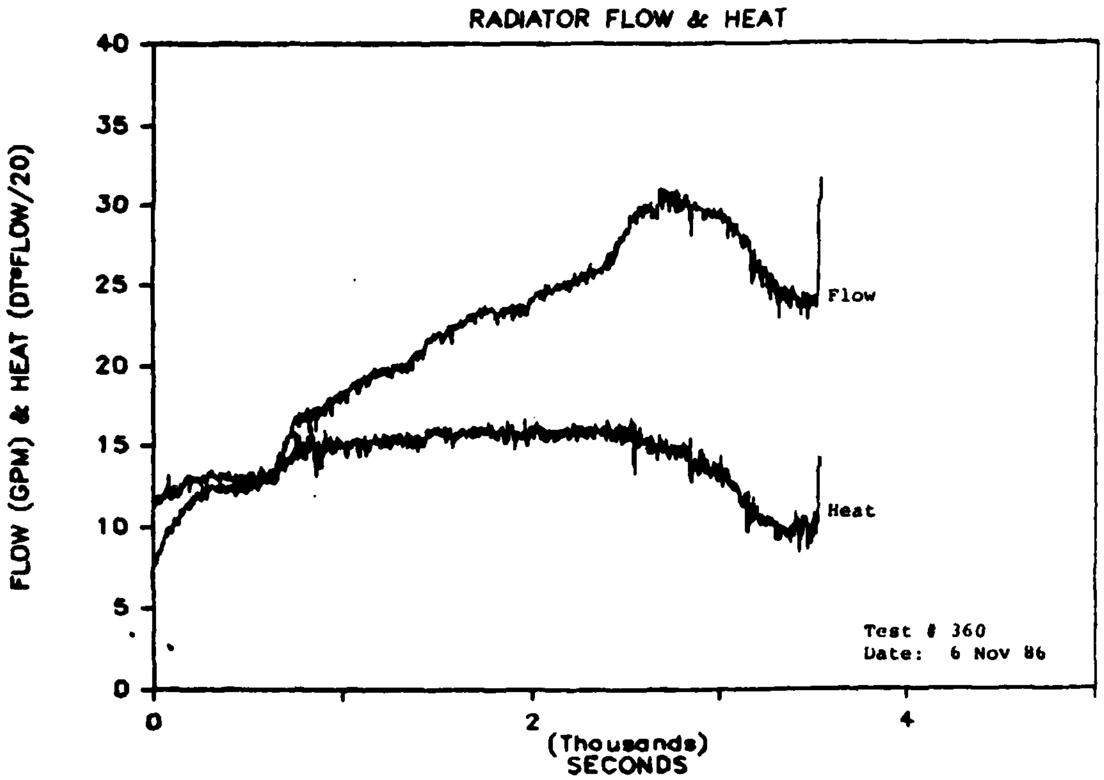
EXPERIMENT TWO

RADIATOR AIR 75% BLOCKED



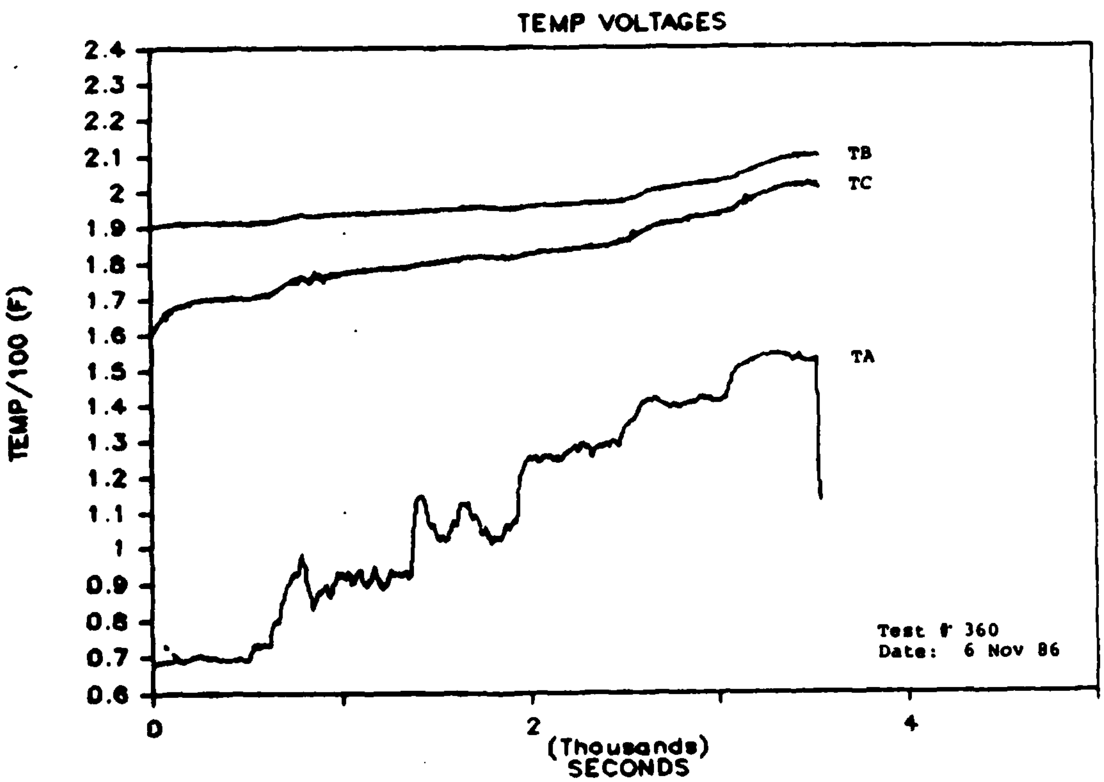
EXPERIMENT THREE

GATE VALVE 60% CLOSED



EXPERIMENT THREE

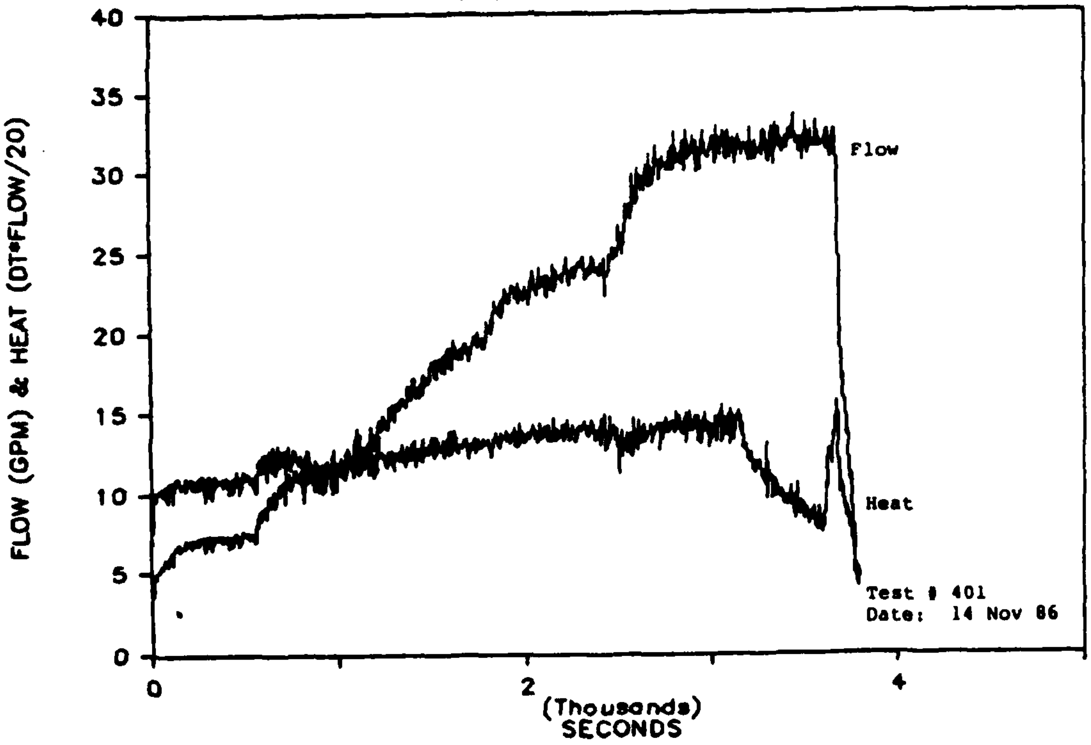
GATE VALVE 60% CLOSED



EXPERIMENT FOUR

COOLANT REPLACED BY TAP WATER

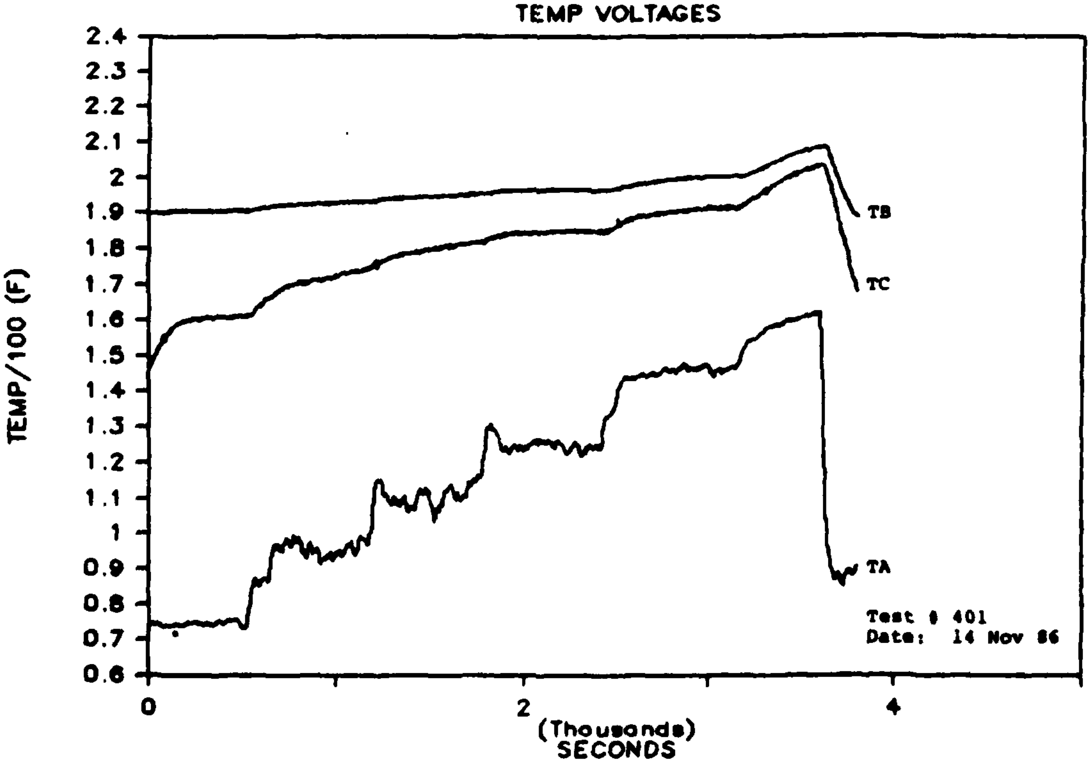
RADIATOR FLOW & HEAT



EXPERIMENT FOUR

COOLANT REPLACED BY TAP WATER

TEMP VOLTAGES



END
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